`Mystery Solved?` Why are there so many beauty quarks produced in hadron colliders?

Mary Bishai

bishai@fnal.gov

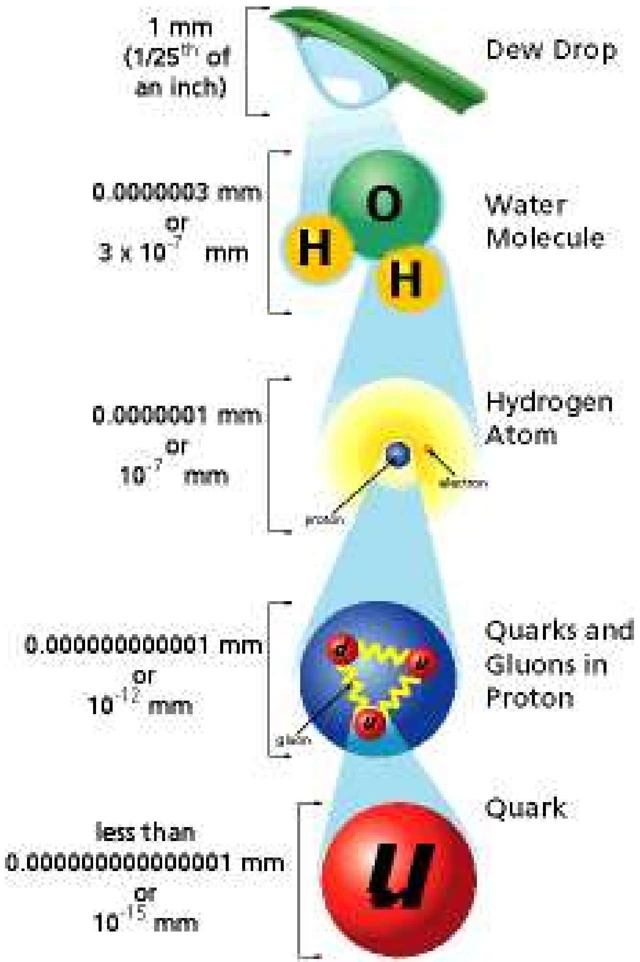
Fermi National Accelerator lab

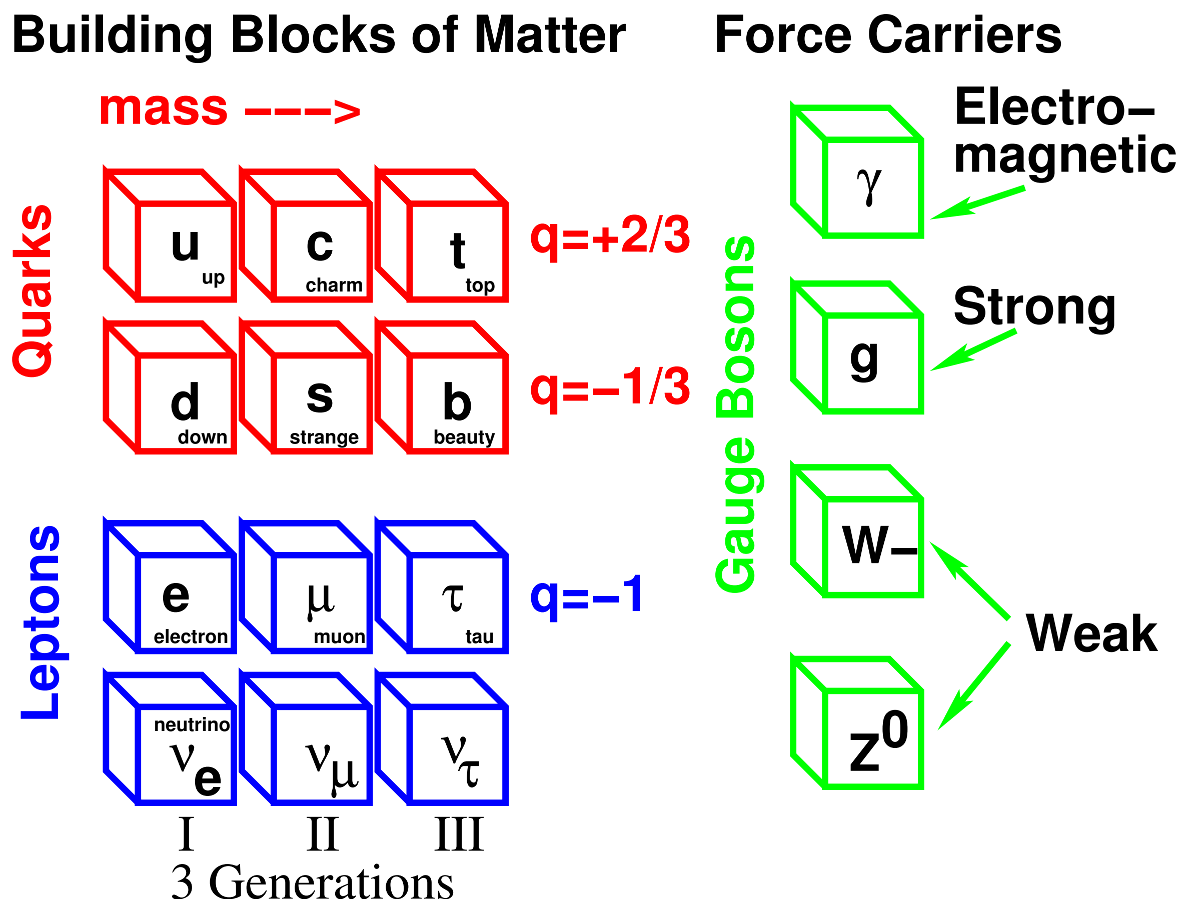
Outline

- General Introduction
- Too Many Beauty Quarks!
- The Theory
- The Accelerator
- The Detector
- A New Measurement
- Conclusions

"Quarks. Neutrinos. Mesons. All those damn particles you can't see. That's what drove me to drink. But now I can see them!"

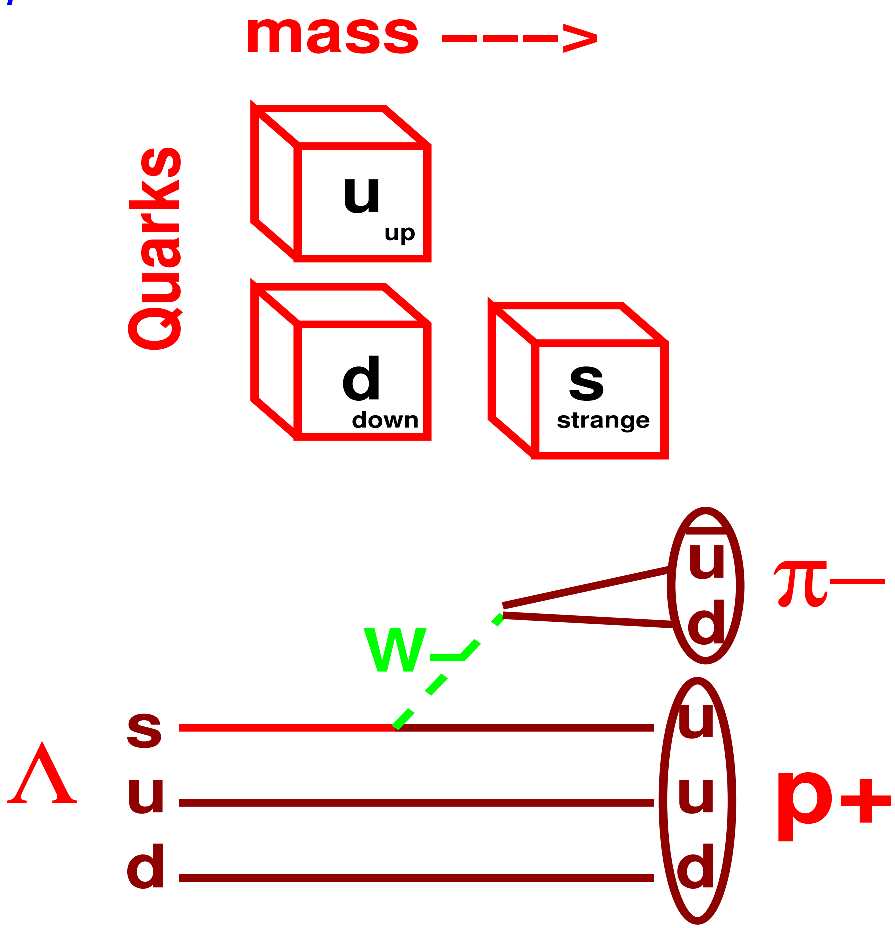
The Standard Model

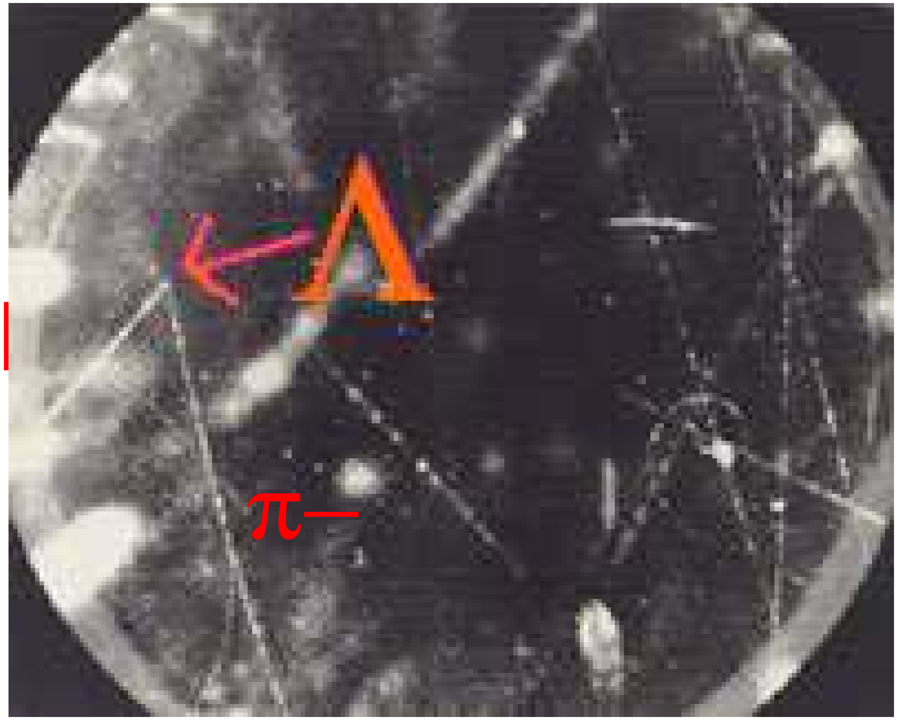




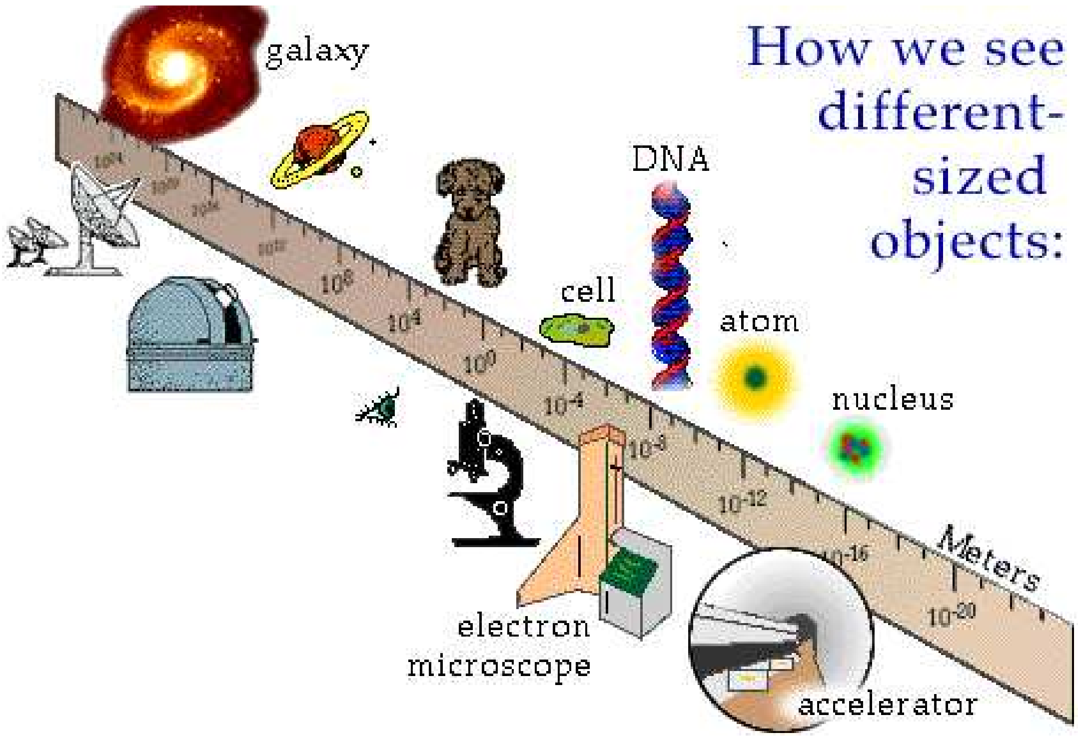
It started with “strange”

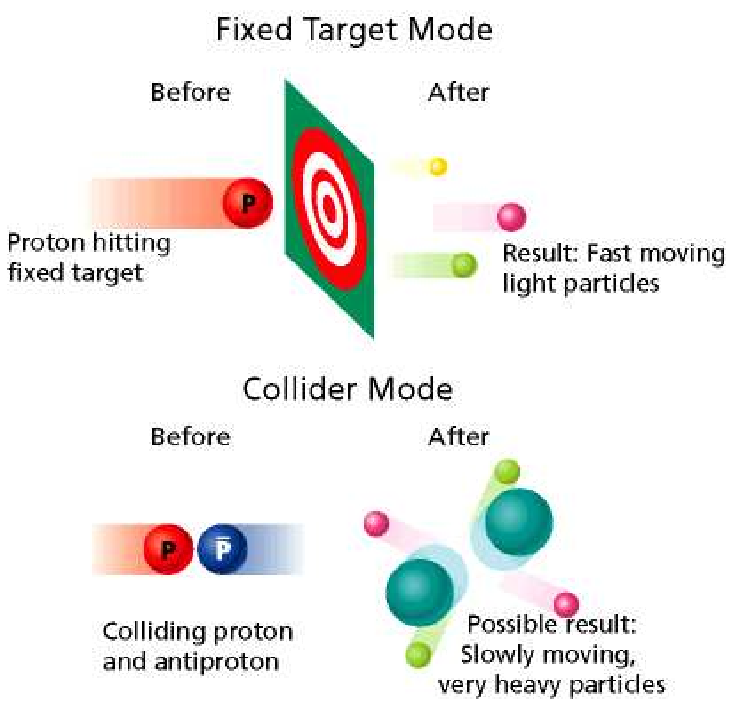
The birth of the quark model started with the discovery of “strange” particles in cosmic rays circa 1947. Below is an example of a “strange” particle:





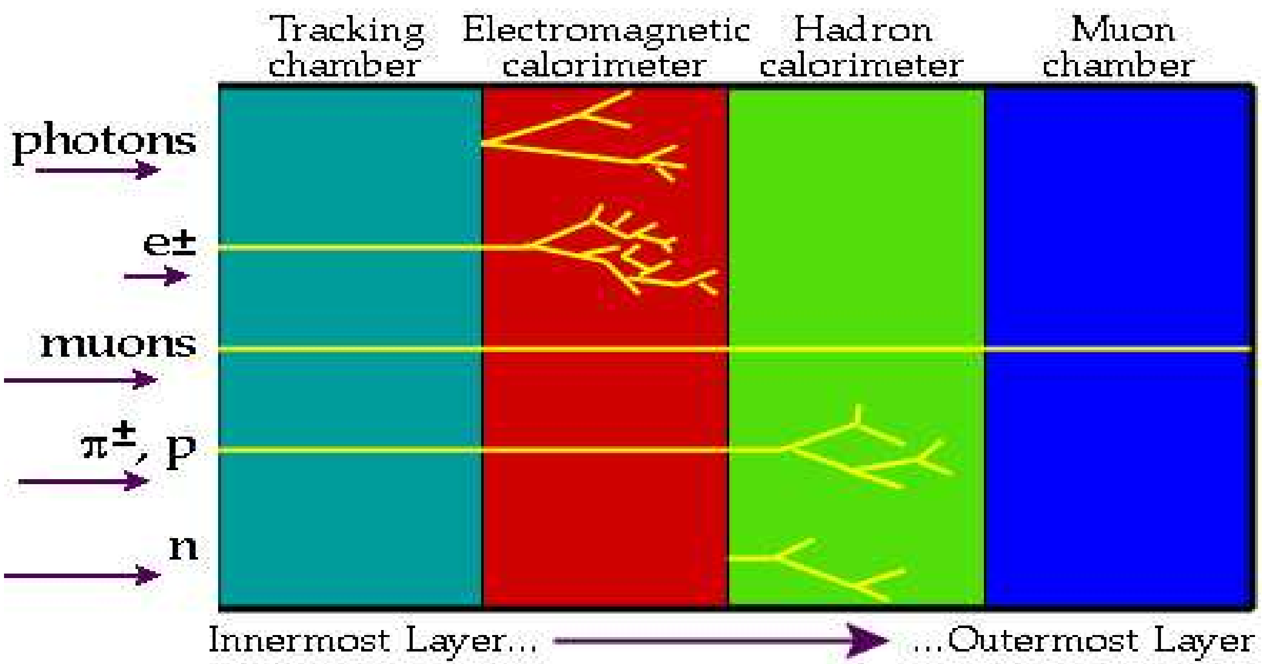
The age of accelerators

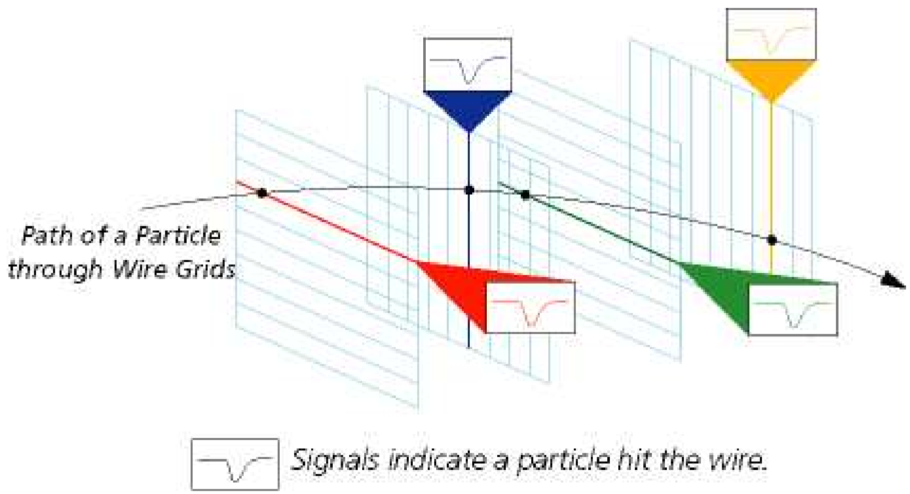


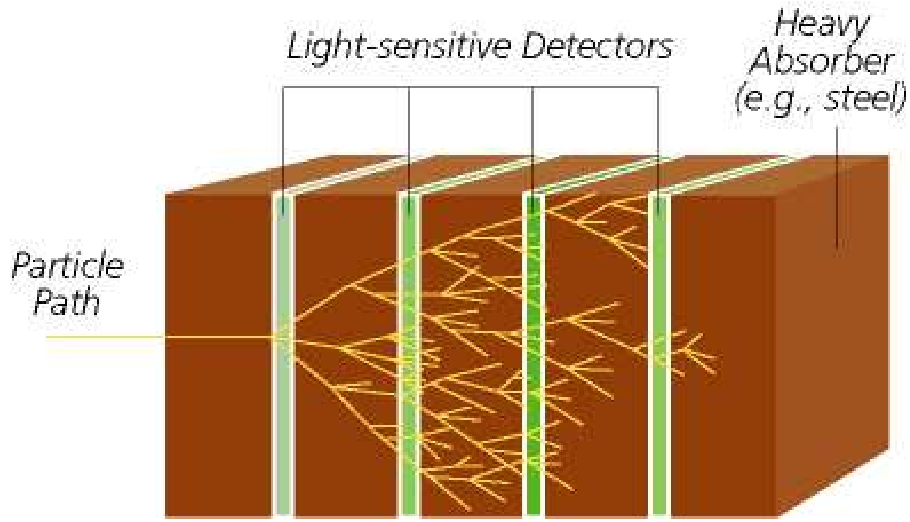


By colliding particles together, we can create different particles that are unstable and shortlived ($E = mc^2$). These particles decay to stable particles such as protons, electrons, and the long-lived muons, $\pi(\bar{u}d)$-mesons and Kaons$(\bar{u}s)$ that were already known from cosmic rays.

Detector basics..

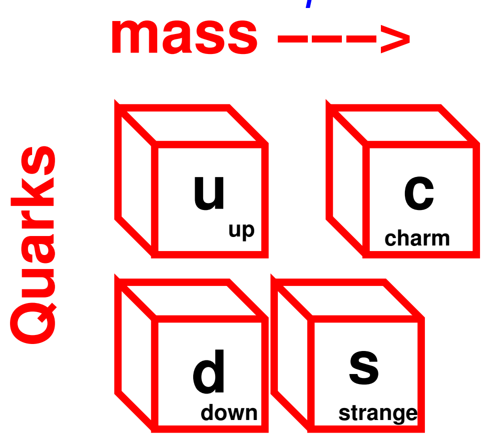


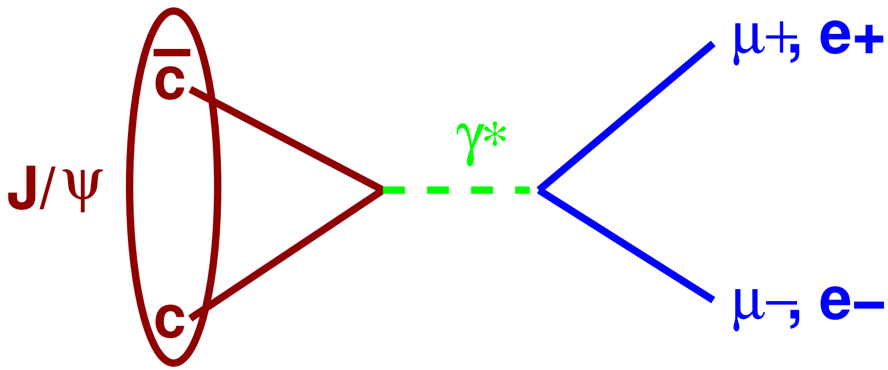


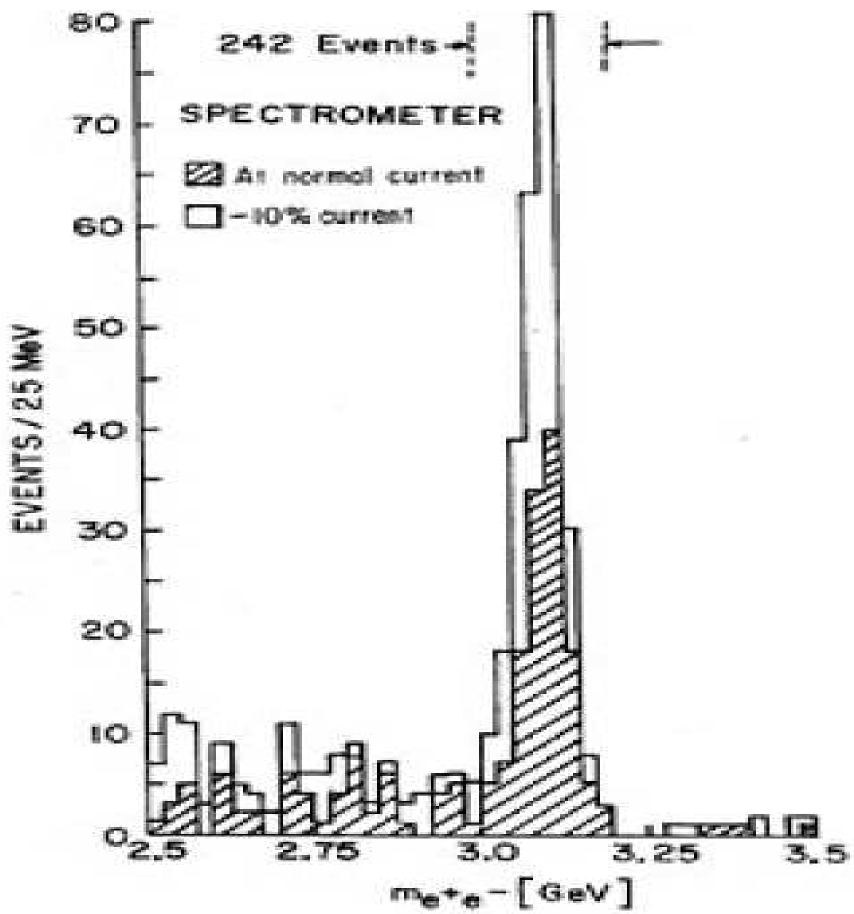


Discovery of the charm quark

In 1974, accelerators at Brookhaven (proton beam on Be target) and SLAC (e^+e^- collisions), see a mysterious bump in the e^+e^- spectrum!





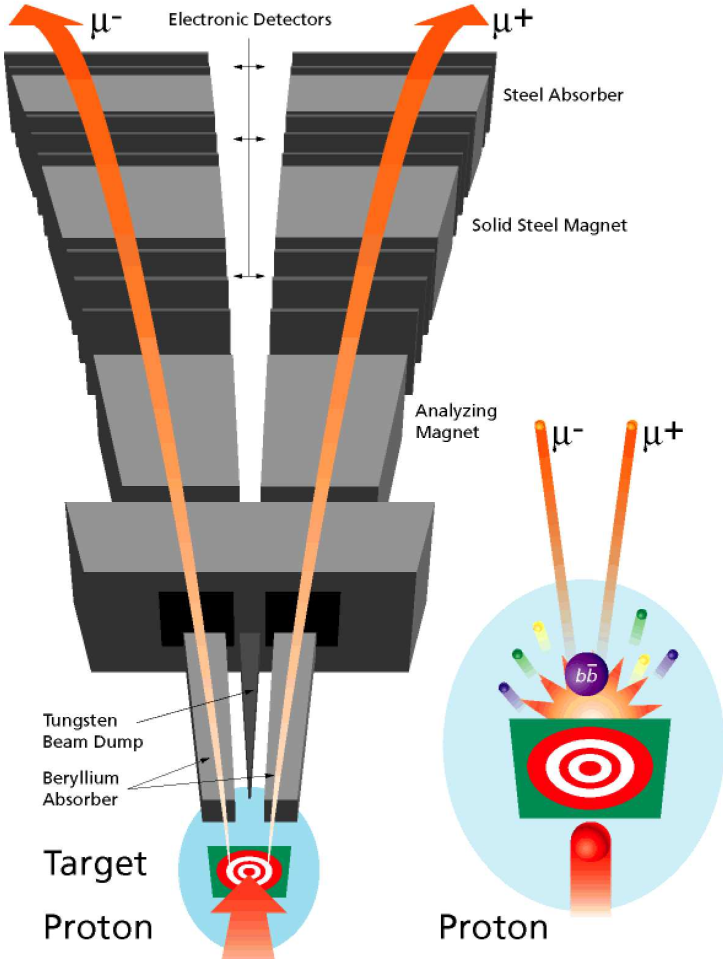


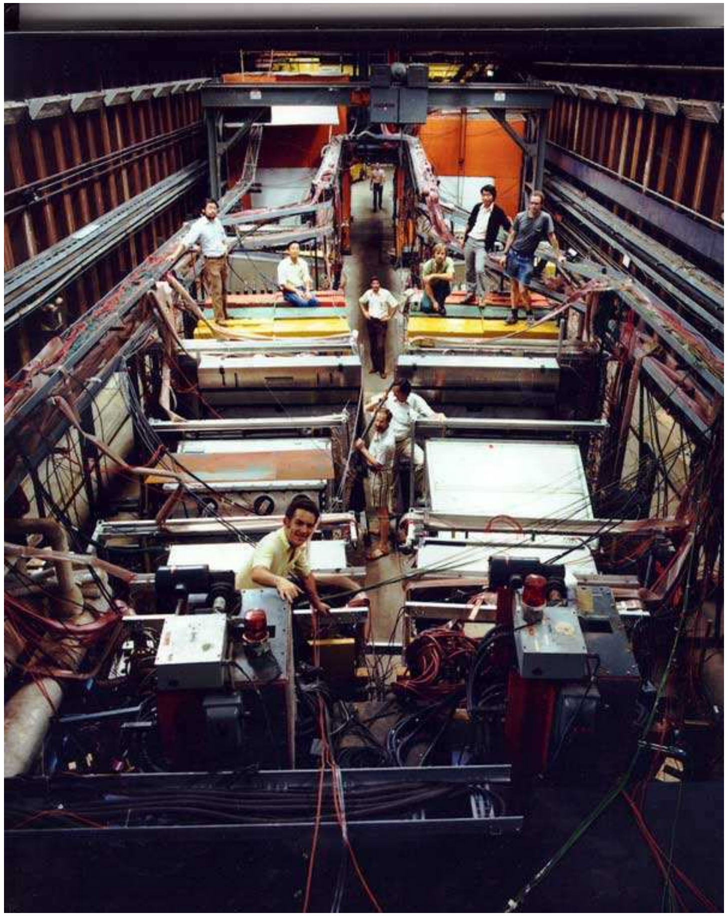
Discovery of the J particle at BNL

(co-discovered at SLAC as the ψ)

The saga continues....

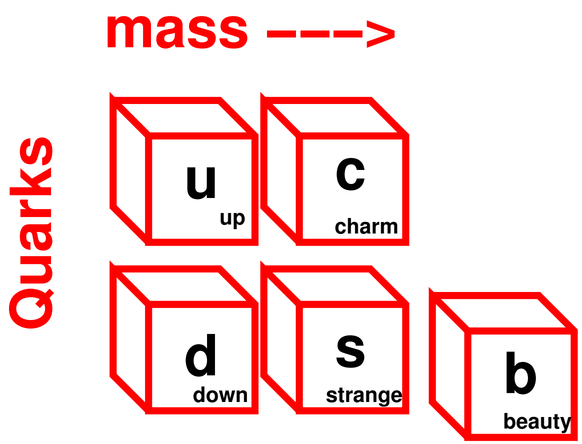
In 1977, an expt with proton beams on targets starts collecting data at Fermi National Accelerator Lab. in Illinois:

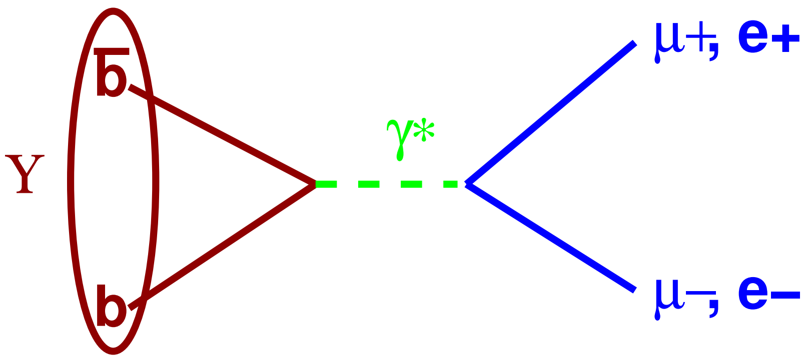


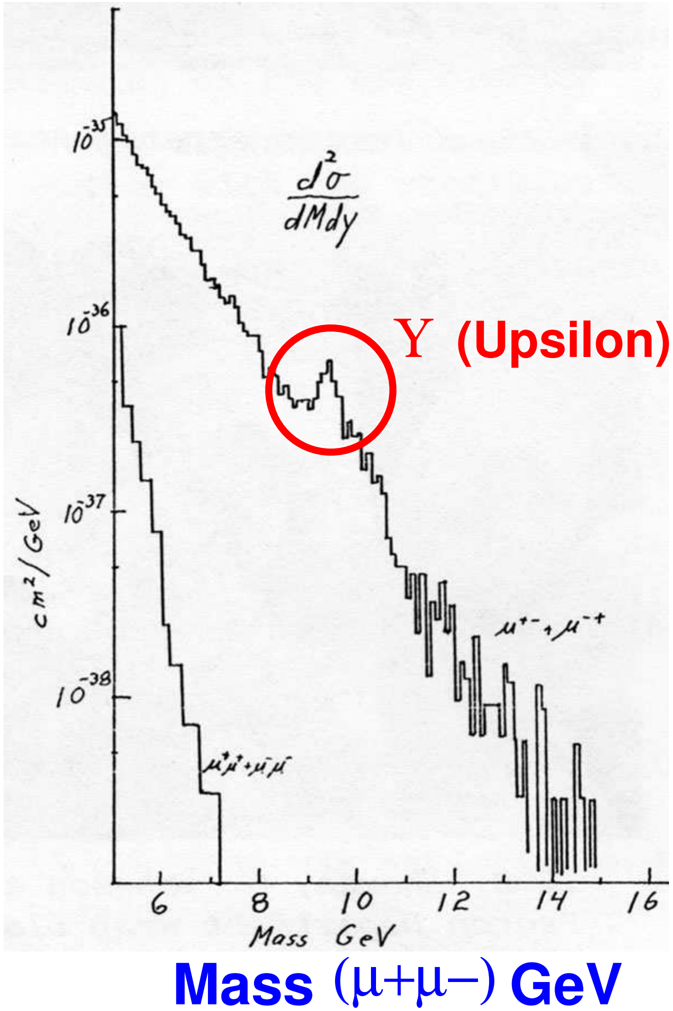


Discovering Beauty

Fermilab sees a bump at higher energy in the di-muon spectrum

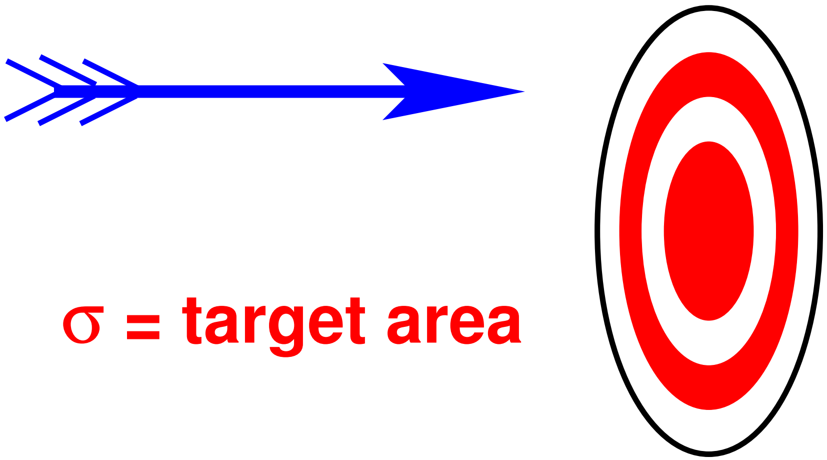






Evidence that yet a third generation exists..

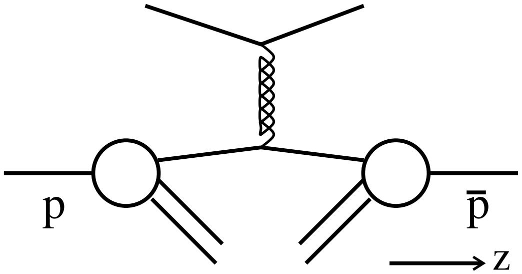
Interaction cross-sections



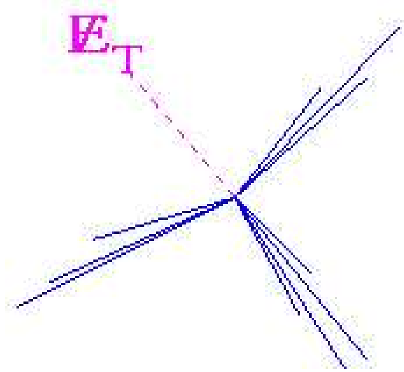
- The cross-section is a measure of the probability that an interaction will occur.
- The term comes from scattering experiments, where the size of the target (like a proton) determines the interaction probability.
- Particle physics *unit of cross-section is a* $barn = 10^{-24}$ *cm*^{2}*.*
- HEP cross-sections are complicated quantities, since they depend on the nature of the target and incident particle, the type of interaction involved: EM, strong, weak, the center of mass energy...etc.

Measurement variables

Hadronic collisions are a hard scattering of a beam of quarks, antiquarks, gluons



- The total COM energy and momentum, $\sum E$, $\sum \vec{\mathbf{P}}$ are unknown



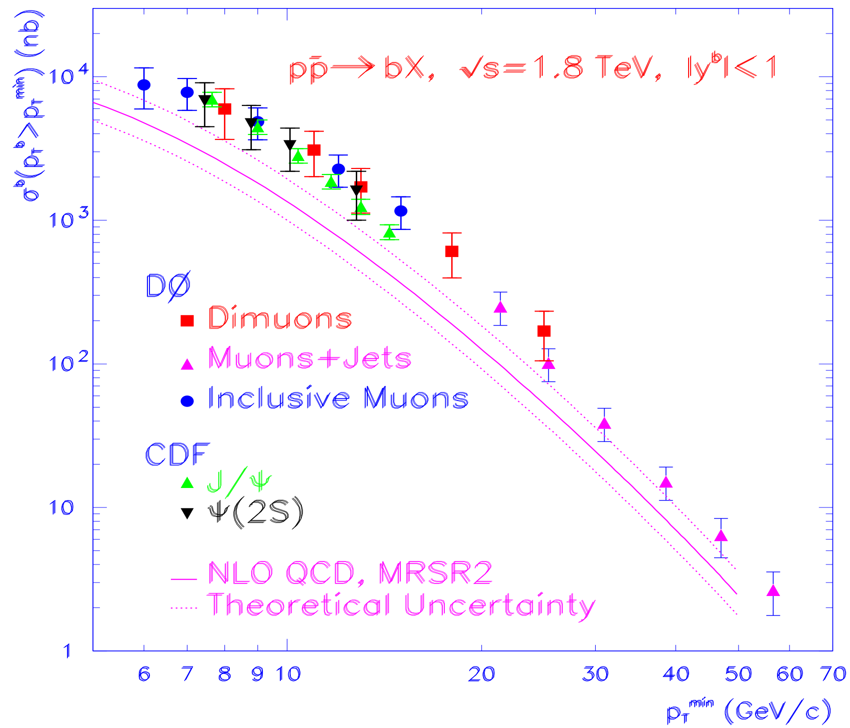
- BUT, there is no momentum component <u>transverse</u> to the colliding beams, therefore, $\sum \mathbf{E_t} = 0$

- Kinematic variables used in collider physics are
  - The component of <u>momentum transverse</u> to the beam ,p_T.
  - The <u>rapidity</u> $y = 1/2 \ln(E + p_z)/E - p_z)$
  - When $m << p_t \Rightarrow y \approx \eta = -1/2 \ln \tan \theta/2$, <u>pseudorapidity</u>.

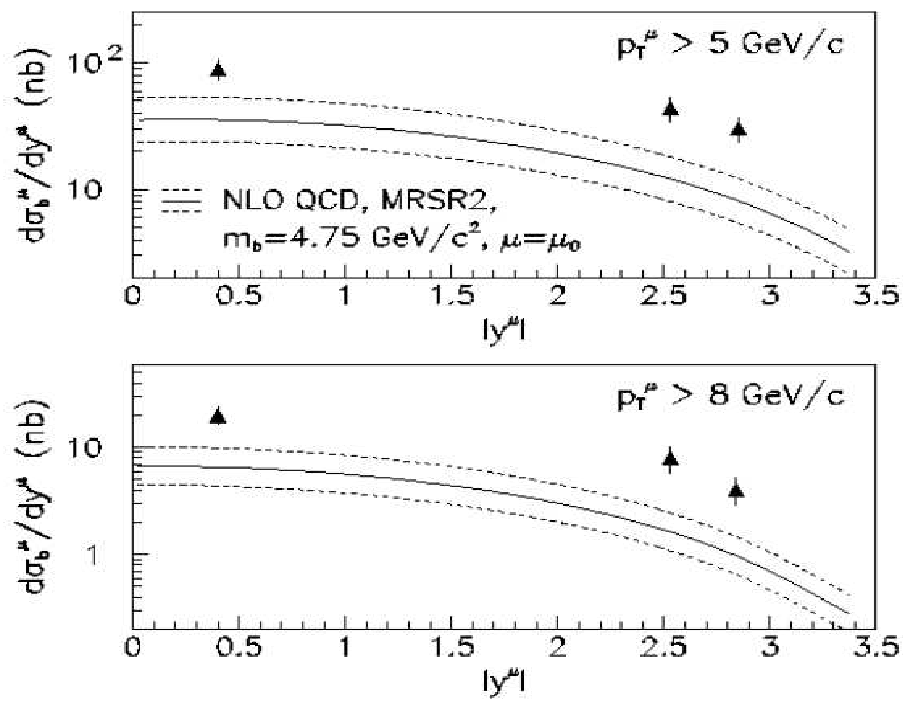
20 years after the discovery of b

- *<u>Circa 1989</u>, b production cross-sections at the Tevatron proton-antiproton collider were observed to be $> 2\times$ larger than theory predictions. By 1997, more data had been collected but only a small portion of the b hadron inclusive cross-section, $p_T > 6.0$ GeV/c, had been probed.*

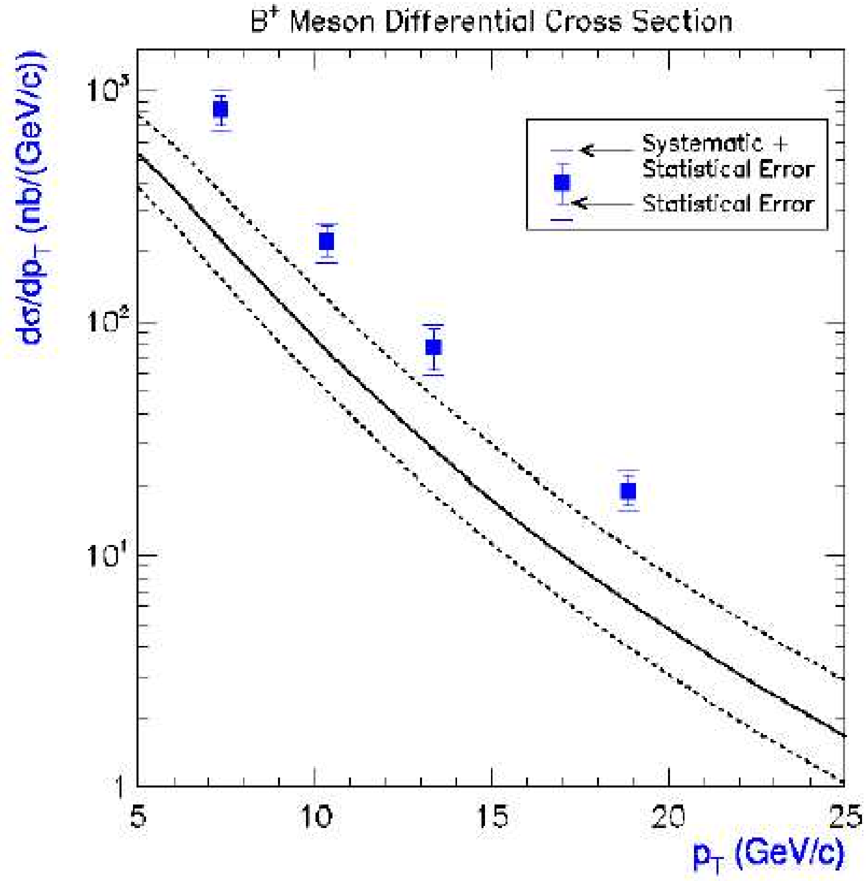
$\sigma(p\bar{p} \to bx)$ for $(p_T > p_T^{min})$



$d\sigma/dy$ vs y^μ (inclusive μ from D0)



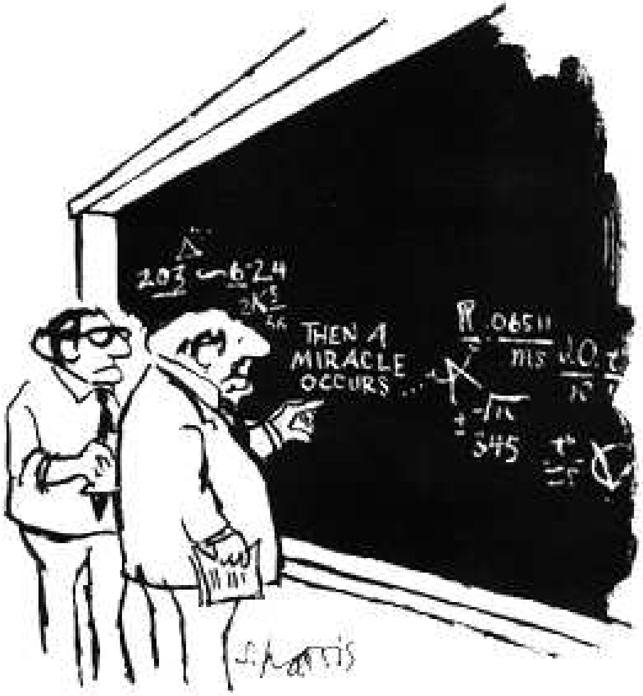
Unanswered questions..



- Is the data wrong? - different measurements, different experiments...
- Is this evidence for new physics? Supersymmetric particles?
- *What is going on with the 70% of the cross-section that hasnt been measured?*

Is this a *shape* or *normalization* problem?

THE THEORY

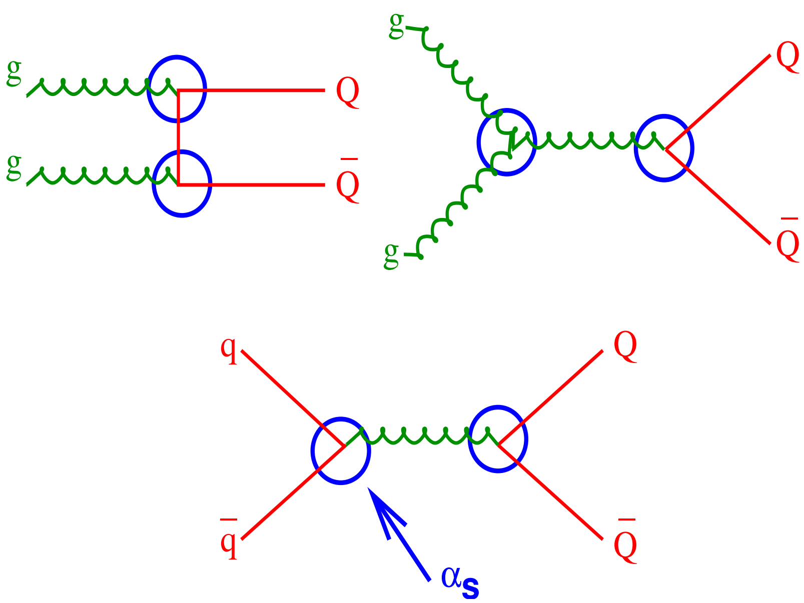


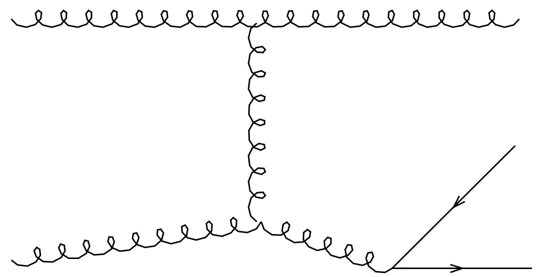
"I think you should be more explicit here in step two."

Strong Production of Quarks

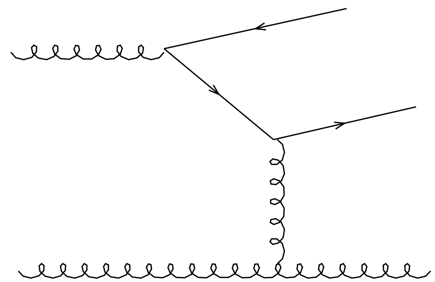
Quantum Chromodynamics describes the theory of strong interactions:

Leading order diagrams: $\mathcal{O}(\alpha_s^2)$





NLO $\mathcal{O}(\alpha_s^3)$: Gluon splitting



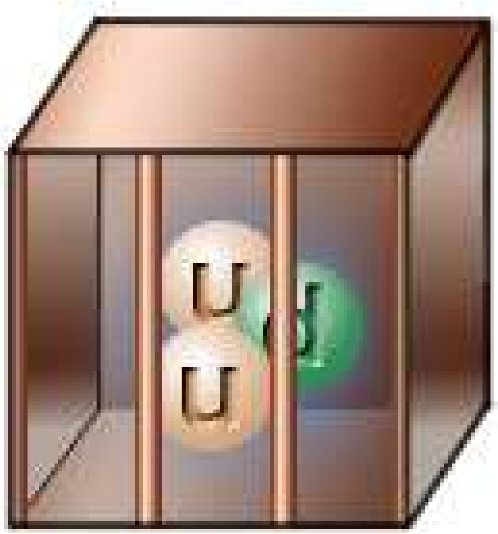
NLO $\mathcal{O}(\alpha_s^3)$: Flavour excitation

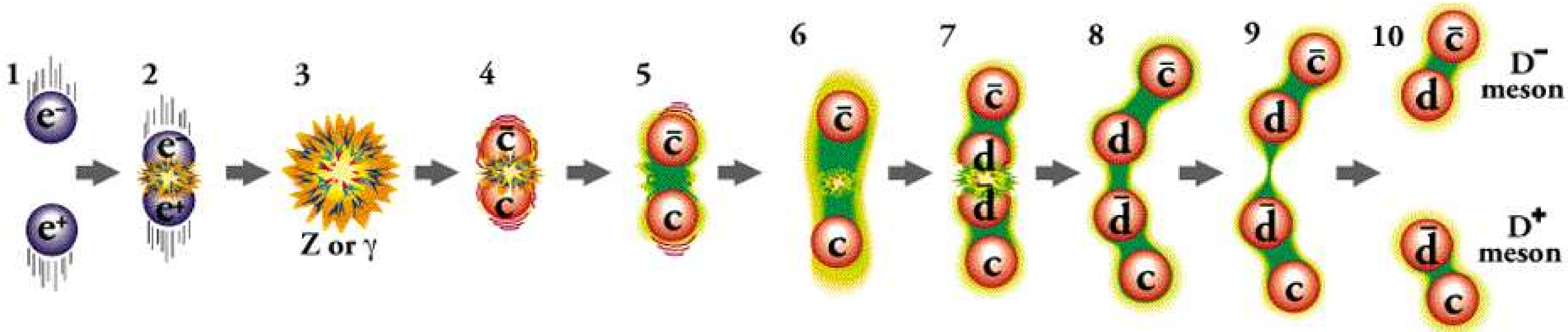
- $\sigma(q\bar{q} \rightarrow Q\bar{Q})$ and $\sigma(gg \rightarrow Q\bar{Q})$ are calculable only when $\alpha_s < 1$
- For example: $\sin(x) = \underbrace{x}_{LO} - \underbrace{x^3/3!}_{NLO} + \underbrace{x^5/5!}_{NNLO} - ...$

Quark/Gluon Confinement

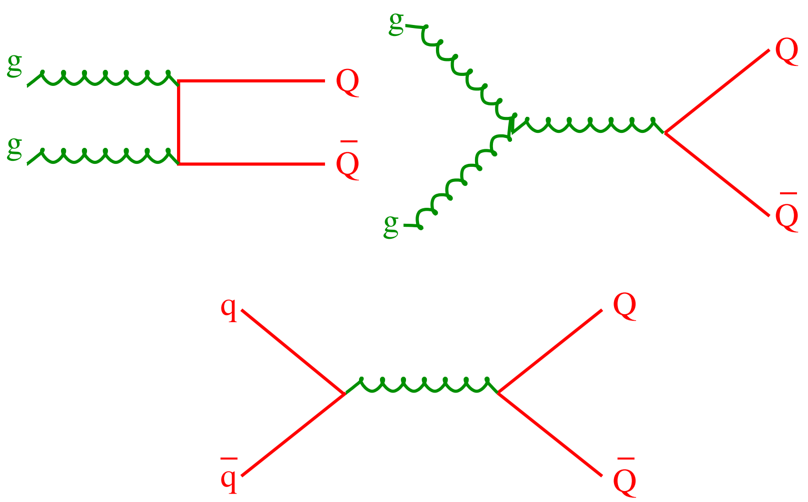
BUT: There are complications with the theory predictions

- Quarks and gluons are "confined" within hadrons.
- The colliding quarks and gluons are in protons (anti-protons)
- The final state quarks "fragment" into baryons (qqq) or mesons $(q\bar{q})$

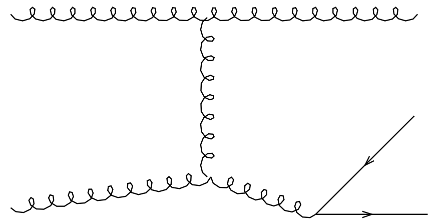




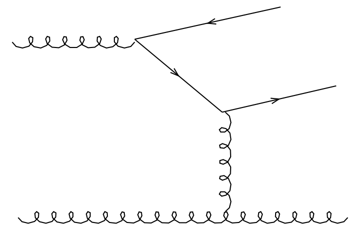
Predicting $p\bar{p}$ Cross-sections



LO Heavy Quark Production



NLO: Gluon splitting



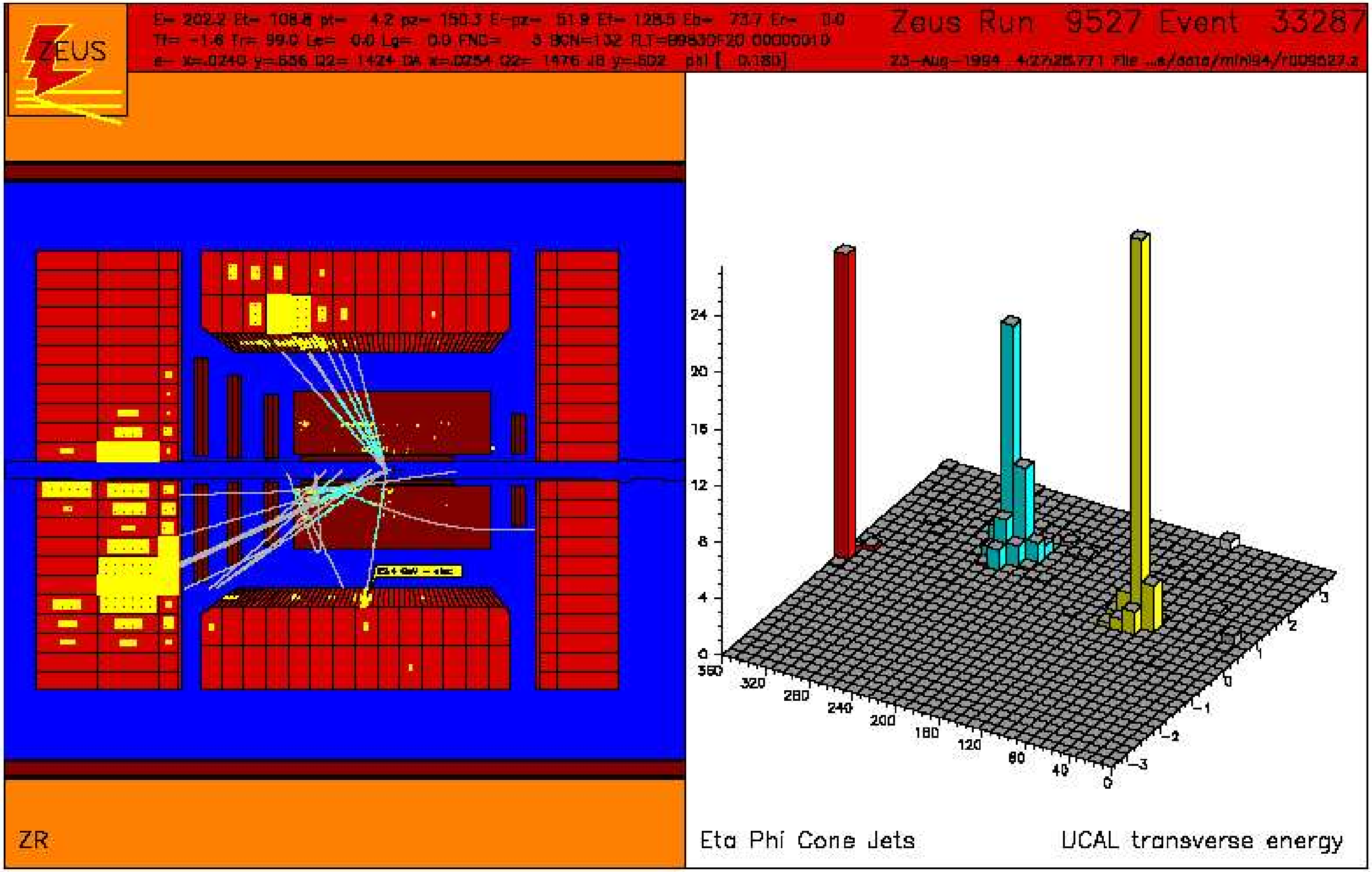
NLO: Flavour excitation

Factorization theorem: factorize physical observable into a calculable part and a non-calculable but universal piece:

$$\underbrace{\frac{d\sigma(p\bar{p}\to BX)}{dp_T(B)}}_{observed} = \underbrace{f^{p,\bar{p}}}_{\text{Proton structure}} \otimes \underbrace{\frac{d\sigma(qq/gg/qg\to bX)}{dp_T(b)}}_{\text{NLO/NNLO QCD}} \otimes \underbrace{D^{b\to B}}_{\text{fragmentation}}$$

Probing proton structure

$e/\mu/\nu$ used to probe *Proton Structure:*



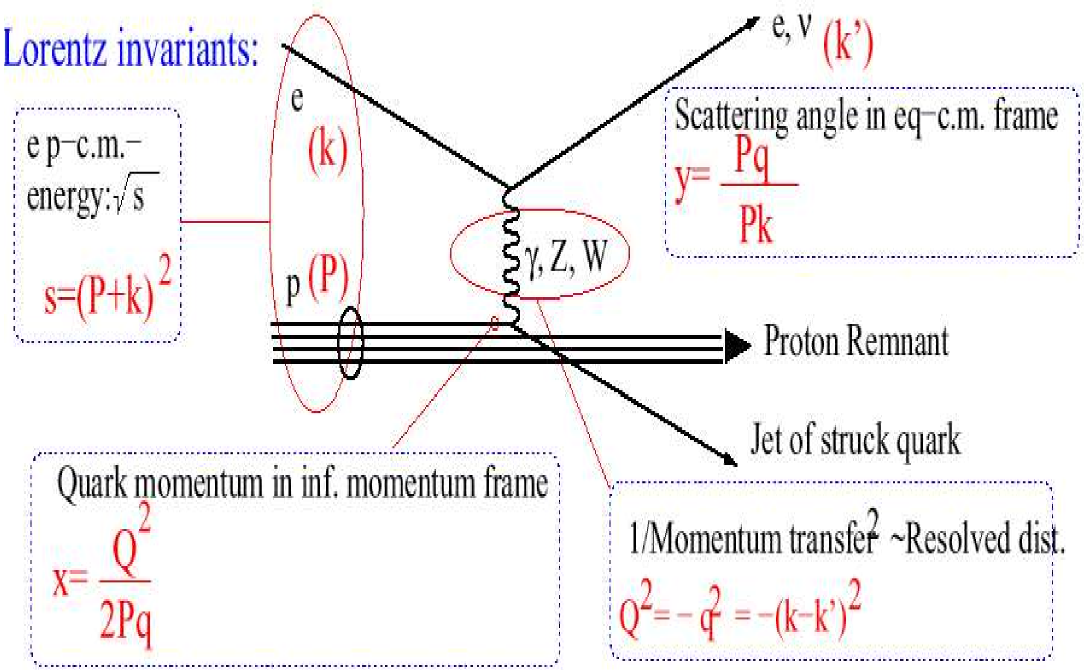
An event from the HERA $e^-, p+$ collider

Modeling proton structure

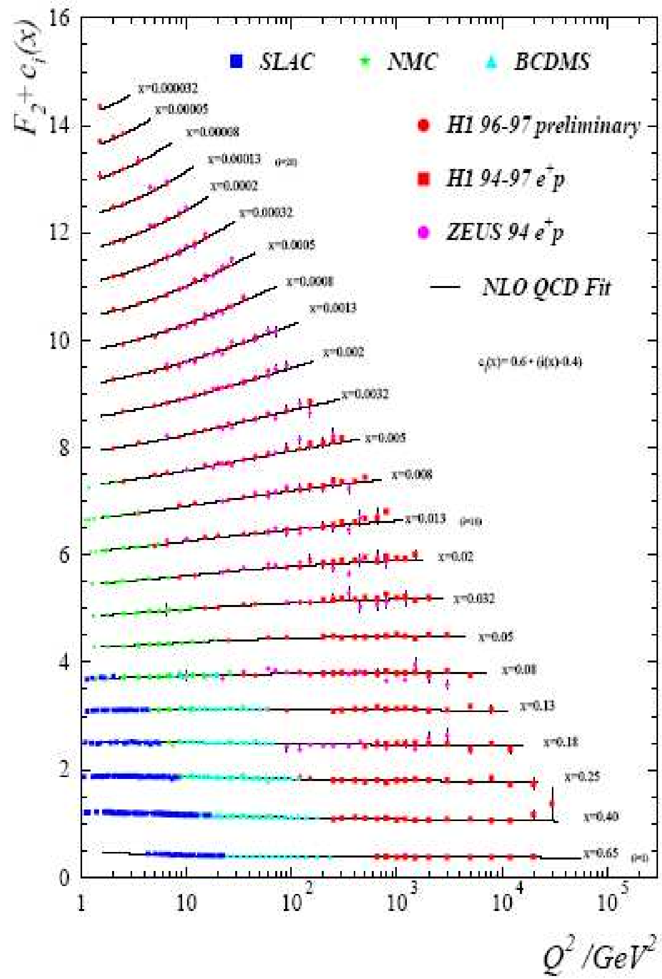
Reactions: NC: $e + p \rightarrow e + X$

CC: $e + p \rightarrow \nu + X$

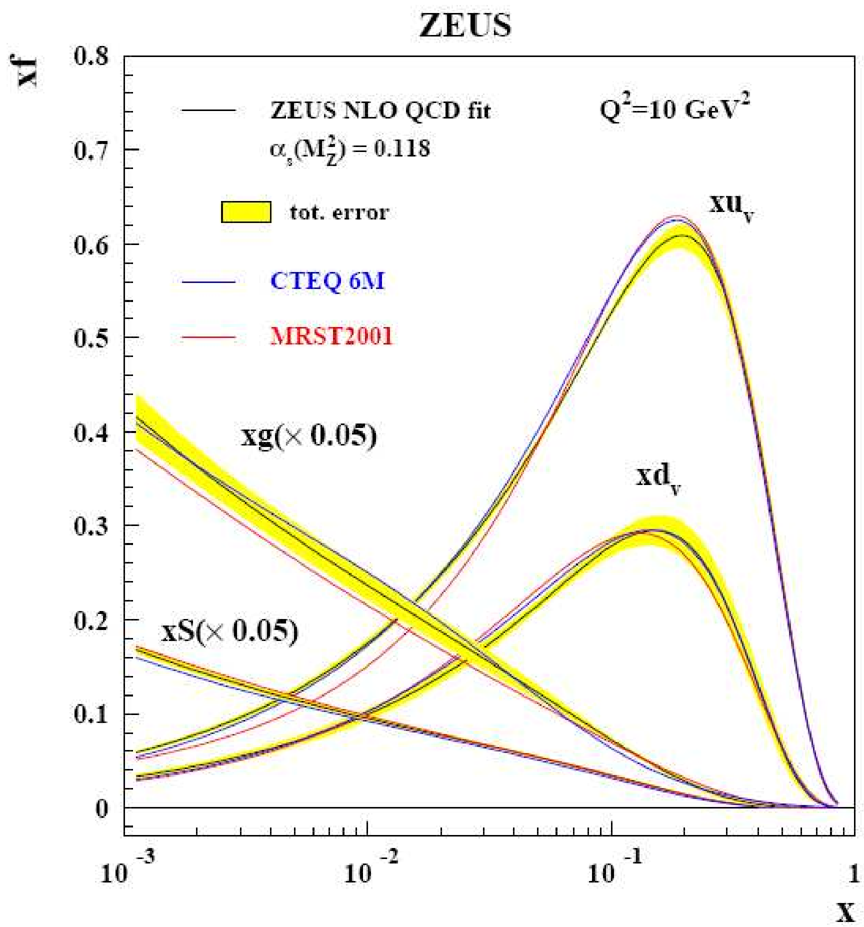
Lorentz invariants:



Relation: $Q^2 = s\,x\,y \quad (M_p << P)$

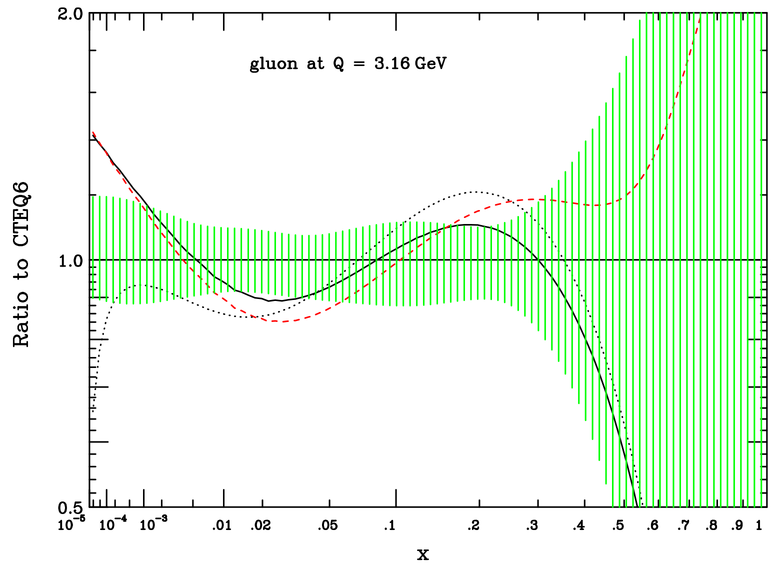


Parton Density Functions (PDF)



Parton densities with uncertainties extracted from fits to the data

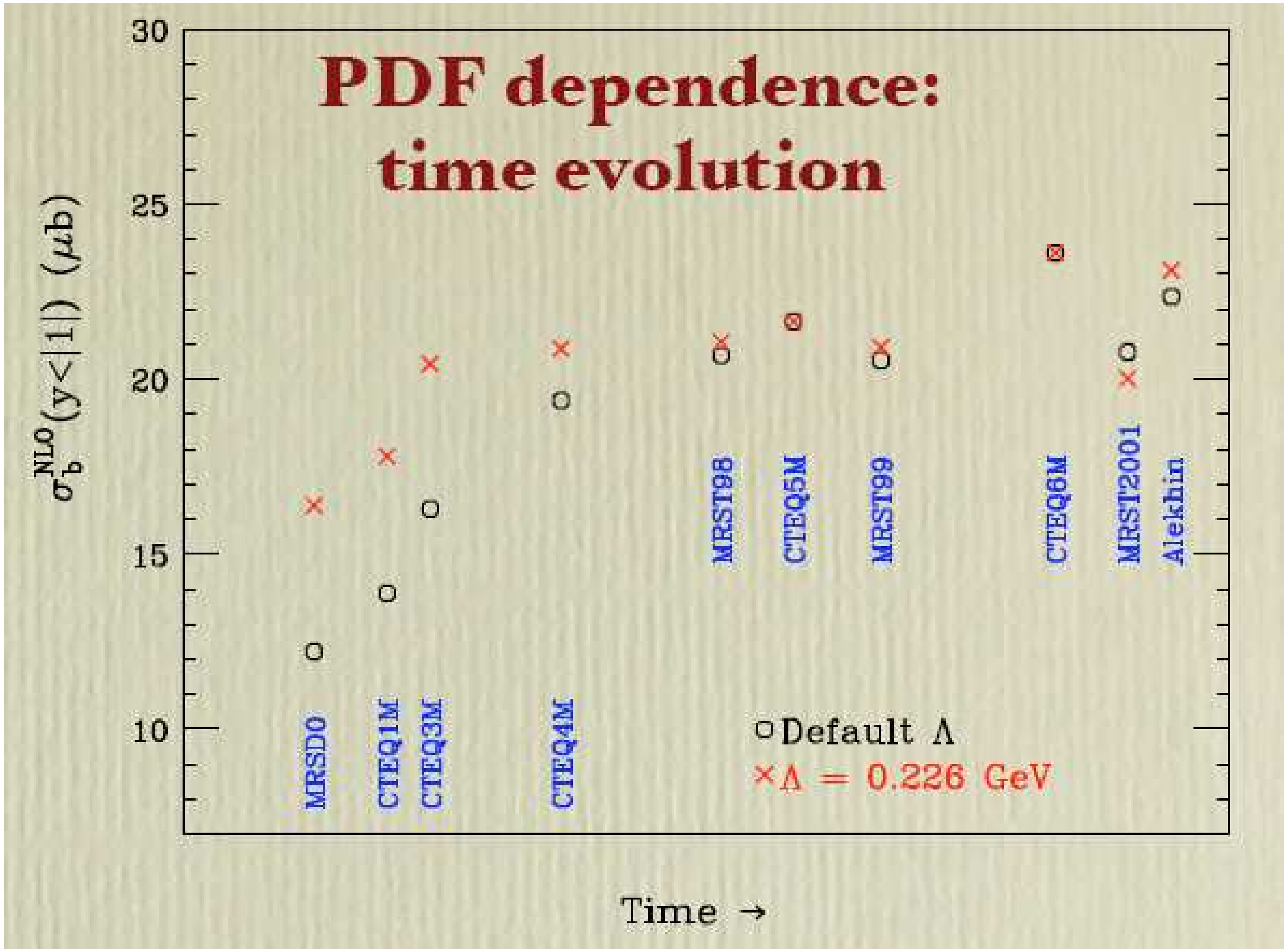
- PDFs $(x f(x, Q^2))$ are universal global fits to data on proton structure that are independent of the measurement process.



Uncertainties on gluonic function

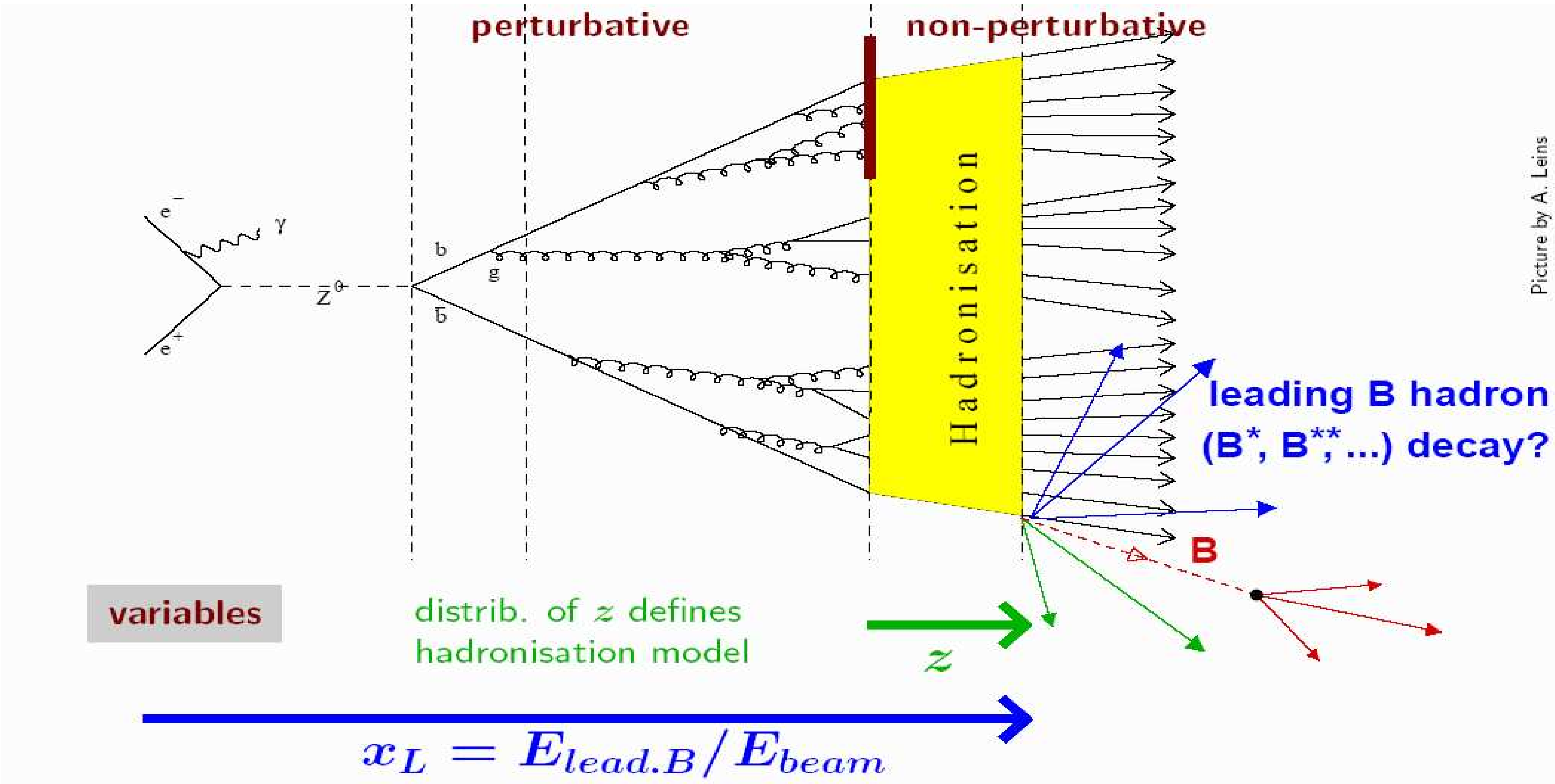
Evolution of PDFs

By 2004, recalculating the cross-section with updated PDFs increases theoretical value by almost 2X!

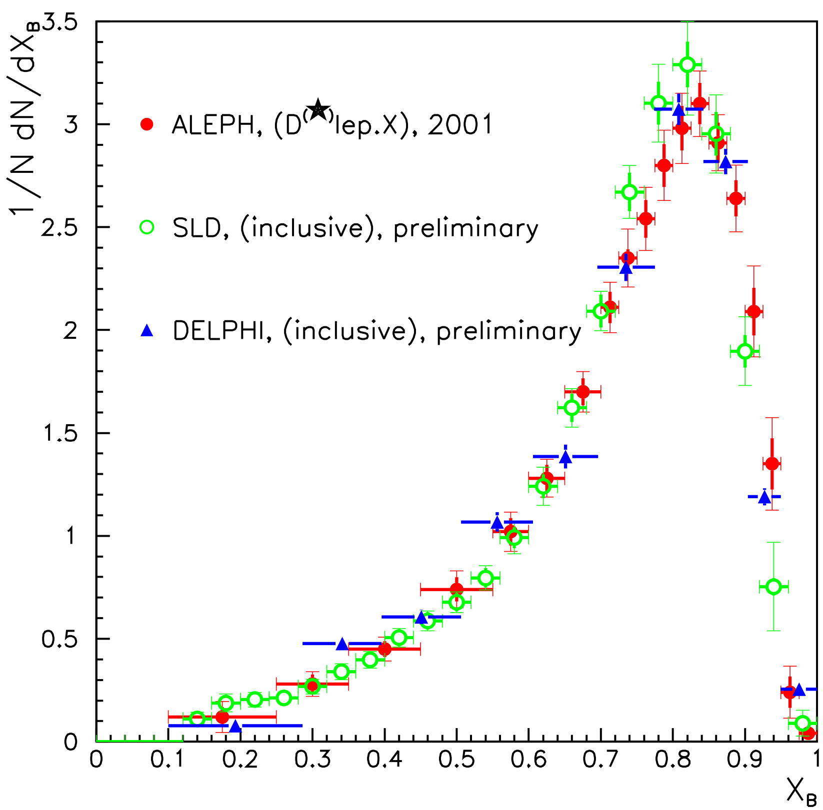


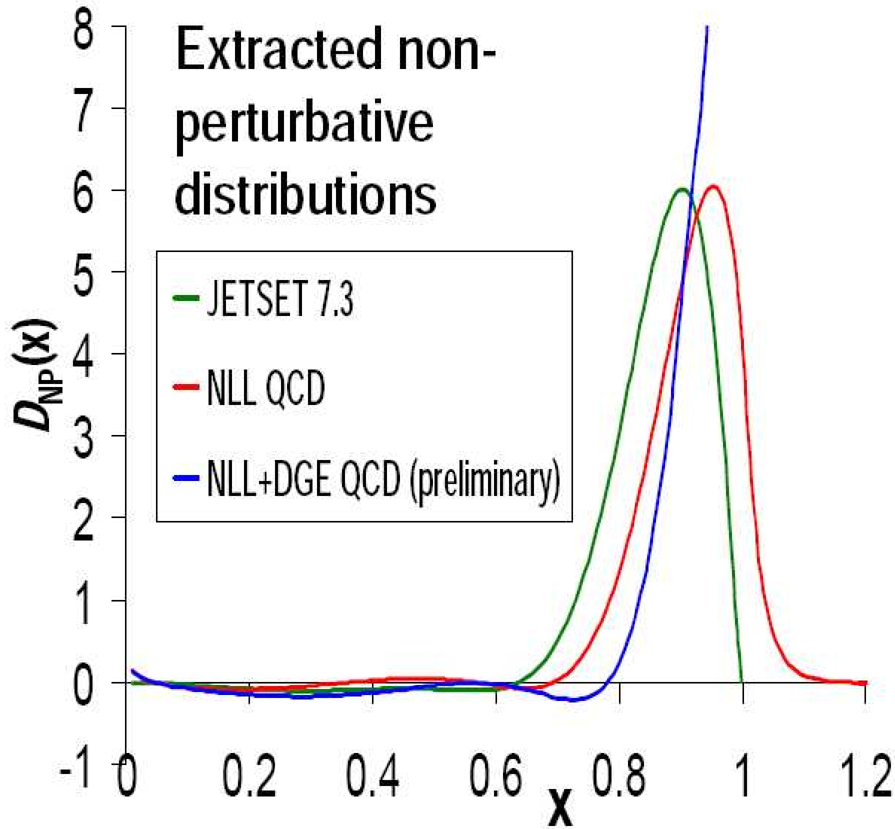
Fragmentation Functions

$$D^{measured}(x) = \underbrace{D^{perturbative}(x)}_{calculable(QCD)} \otimes \underbrace{D^{non-perturbative}(x)}_{non-calculable}$$



Measured Fragmentation Fncns.





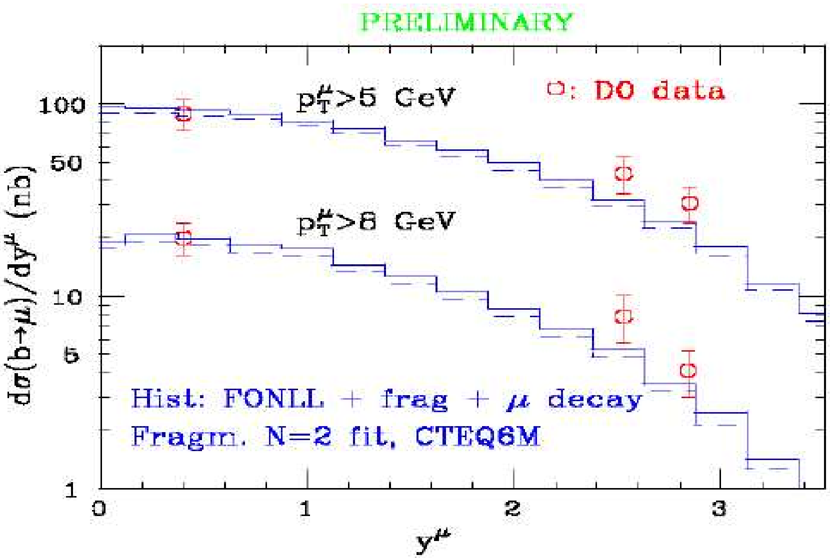
$D(x)$ Measured $D^{non-perturbative}(x)$ Extracted

E. Ben Haim *et. al.* hep-ph/0302157

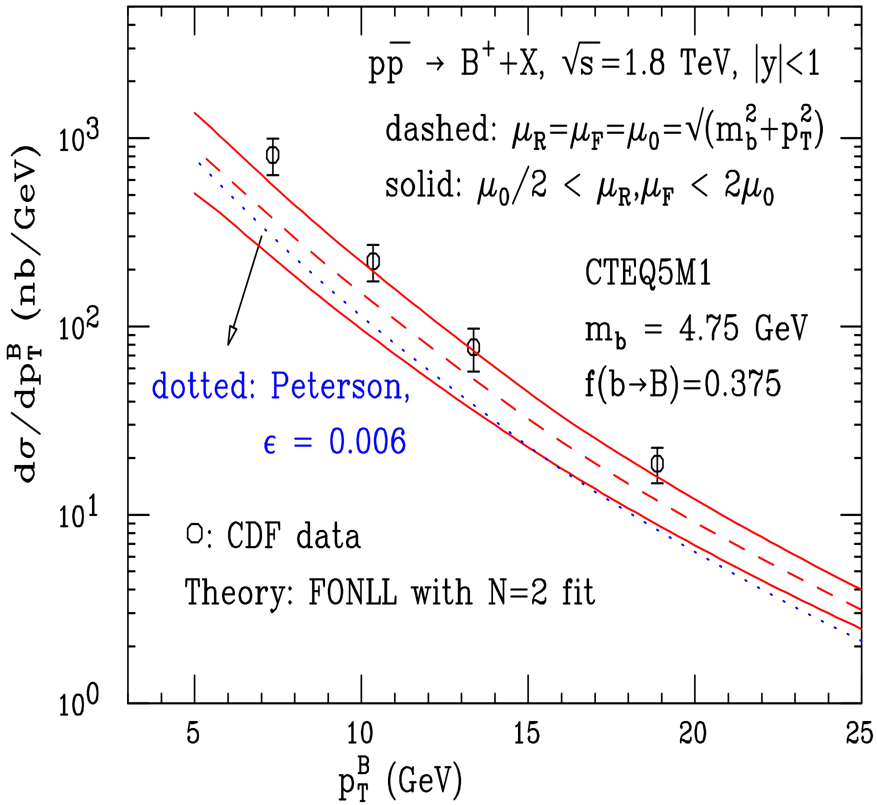
Non-perturbative functions used must match perturbative assumptions

Theory updates...

- 2001: Direct measurement of b fragmentation at LEP.
- 2001: New theoretical method to extract non-pert. fragmentation funcn
- 2002: Updated PDFs



$d\sigma(p\bar{p} \rightarrow B^+X)/dp_T$ vs $p_T(B^+)$ (CDF)



$p_T(B^+)$ GeV/c

Cacciari, Nason hep-ph/0204025 (Run I)

Theory Summary

- Agreement with the Run I b cross-section data for $p_T > 5.0$ GeV/c has greatly improved without the need to invoke exotic sources of excess b quarks. Most of the improvement is due to improved treatment of experimental inputs.
- BUT: There are different theoretical approaches, and new methods to extract the non-perturbative part of fragmentation function. Which is the correct approach?

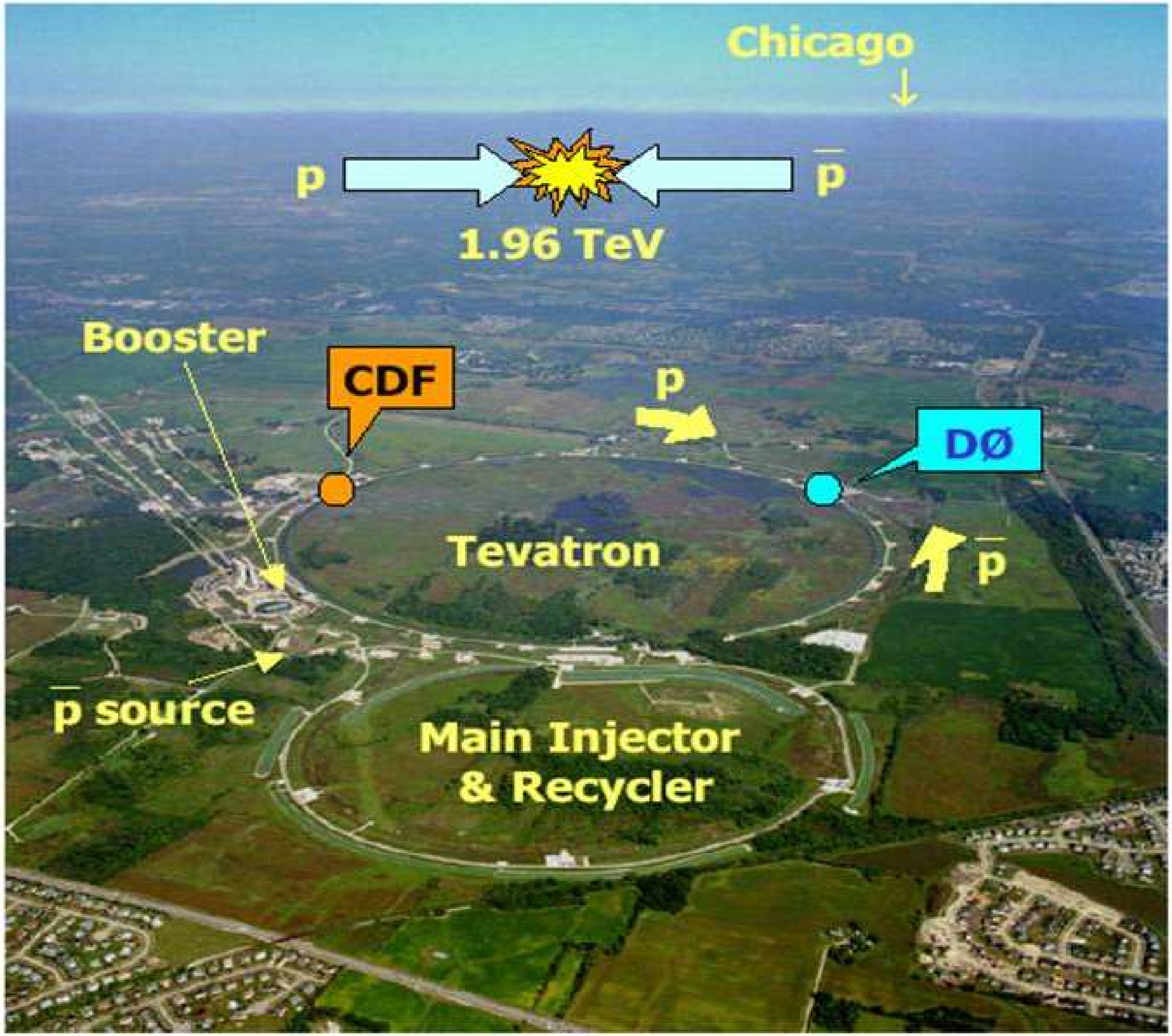
Total cross-sections do not depend on the fragmentation model!

= powerful experimental test of QCD calculations and PDFs.

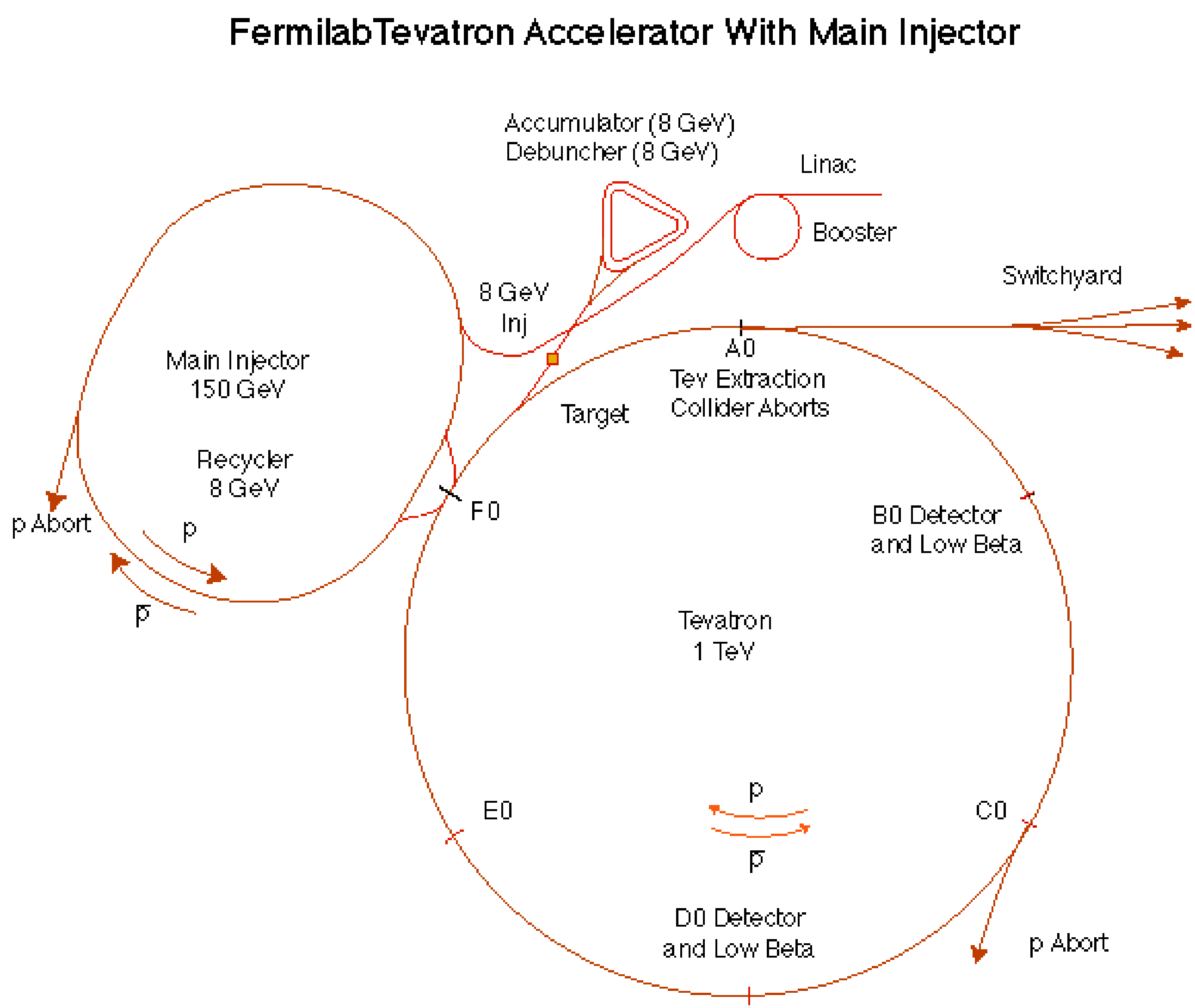
THE ACCELERATOR

"Particles, particles, particles."

The Tevatron



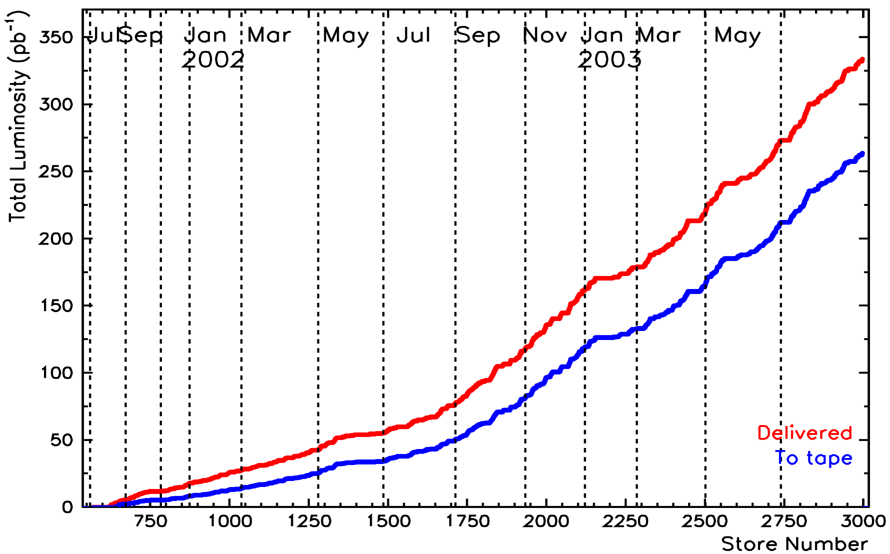
Tevatron Collider Overview

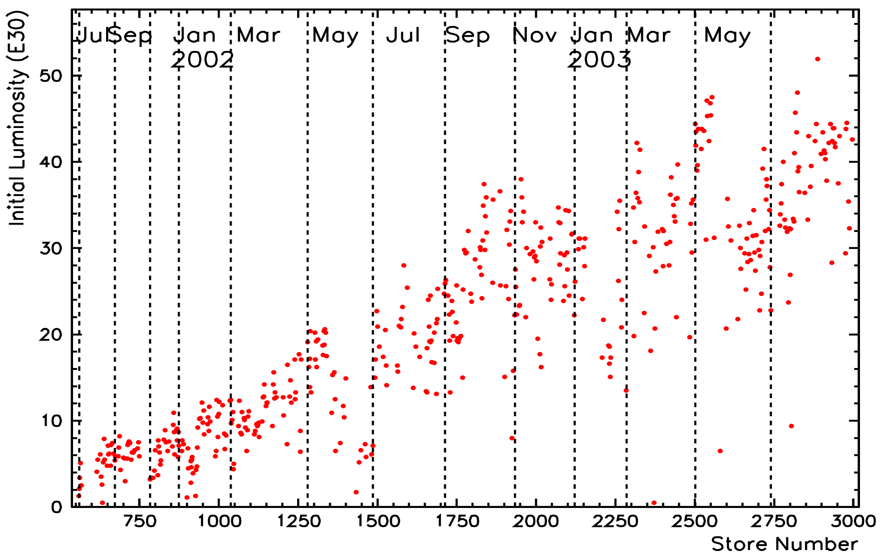


Tevatron Performance

- In 1985, Tevatron collider begins operating @$\sqrt{s} = 1.6$ TeV
- Run I of the Tevatron collected collider data at $\sqrt{s} = 1.8$ TeV from 1992-1995 with $\mathcal{L}^{typical} = 1.6 \times 10^{31}$ [particles] $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. ~ 109 pb $^{-1}$ integrated luminosity was collected by each collider detector. *Event rate = cross-section X luminosity*

Run II : Summer 2001 - present. 2.5X more data already!





THE DETECTOR

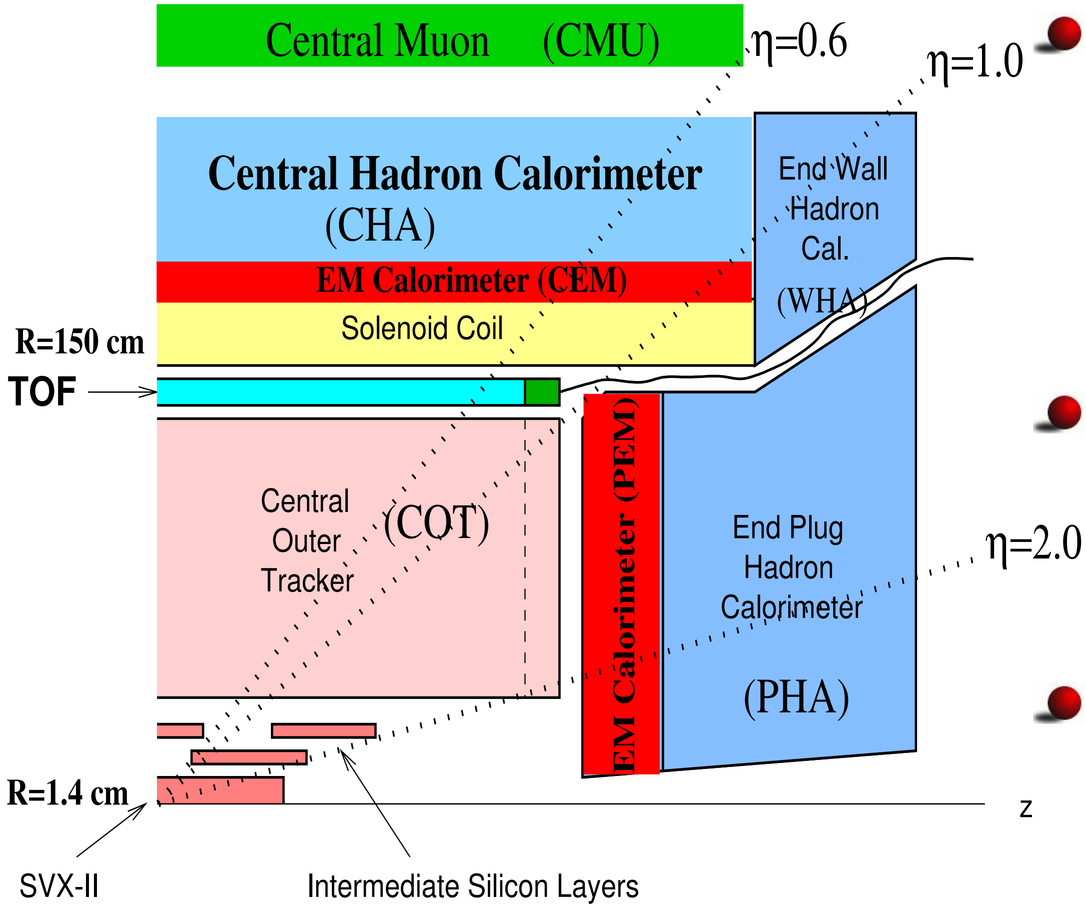
"But don't you see, Gershon - if the particle is too small and too short-lived to detect, we can't just take it on faith that you've discovered it."

The Collider Detector at Fermilab

Run II: 788 collaborators, 62 institutions, 12 countries

CDF Run II - Overview

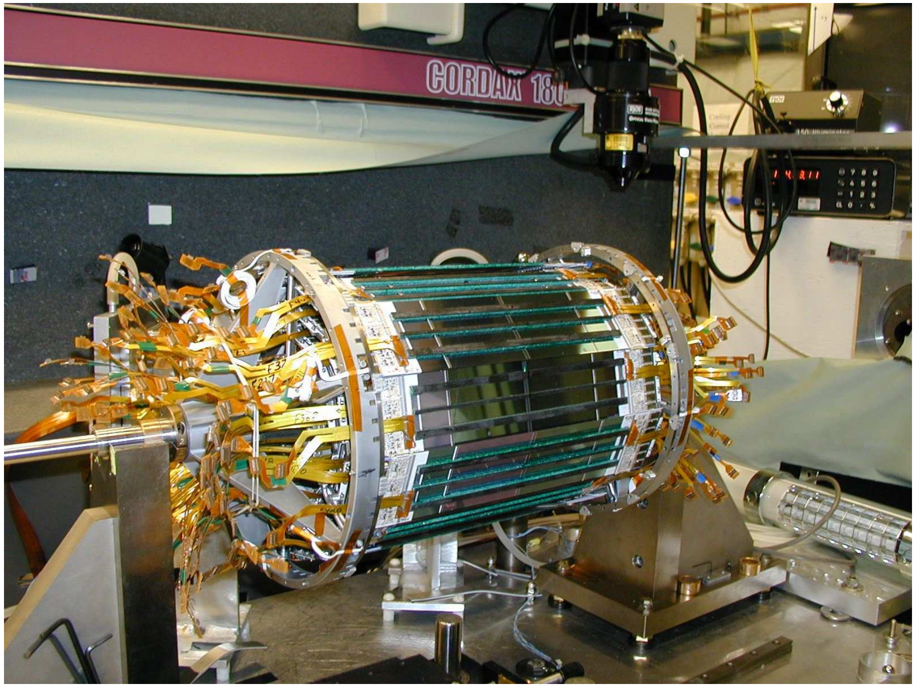
Signals: $J/\psi \to \mu\mu$, displaced b vertices

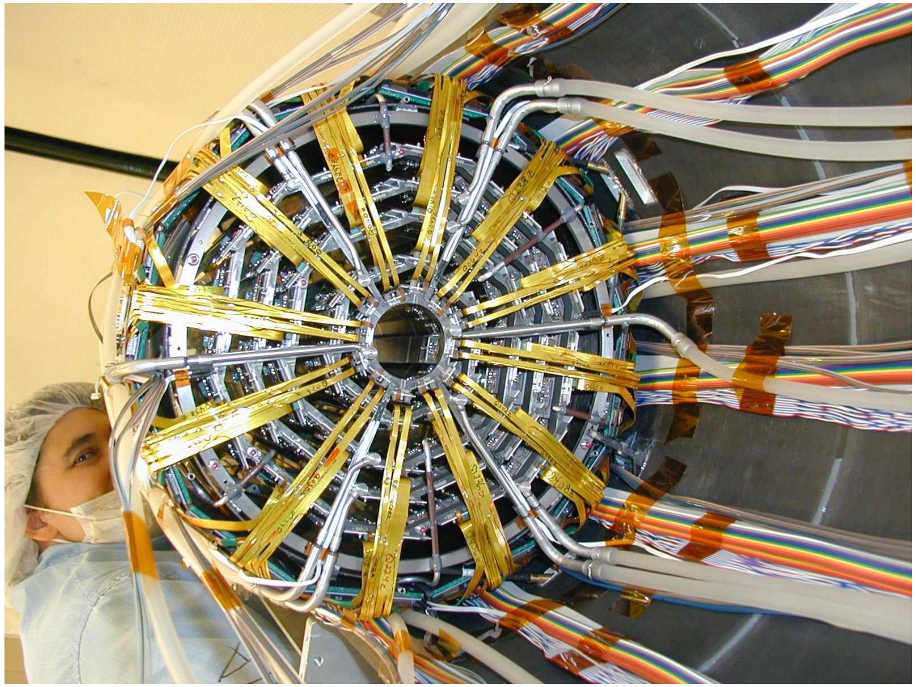


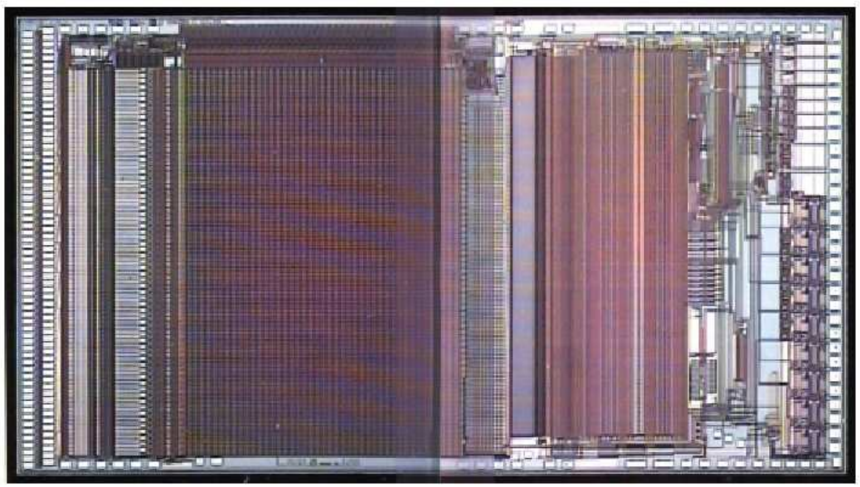
$$\eta = -1/2 \ln \tan \theta/2$$

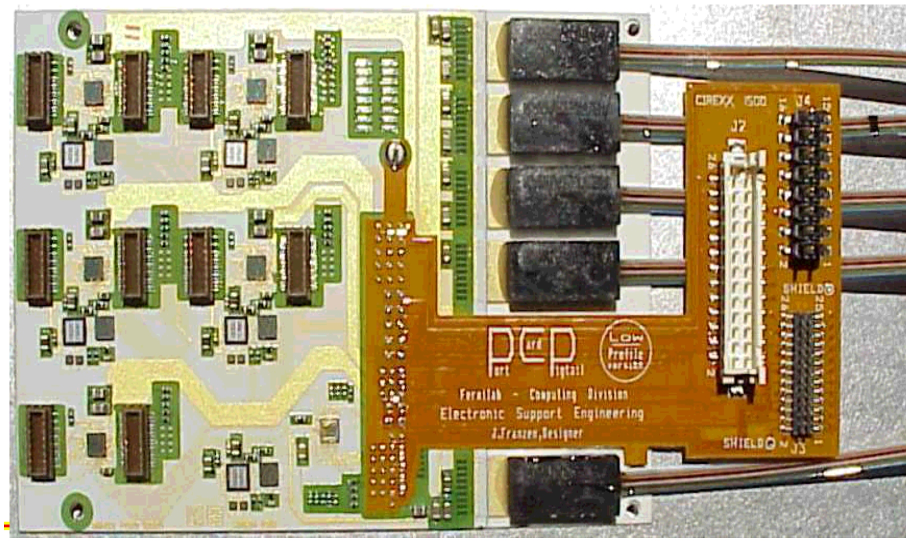
- *Central Muon detector*: Prop. chambers outside central calor. $\sim 5\pi$ interaction lengths.
- 96 layer Central Outer Tracker (COT): $\sigma(p_t)/p_t = 0.003p_t$
- Silicon vertex detector: 8 Layers of 3-D Silicon up to $|\eta| = 2$, 700,000 readout channels, $\sigma(d_0) \sim 20\mu m$

The Silicon Vertex Detector

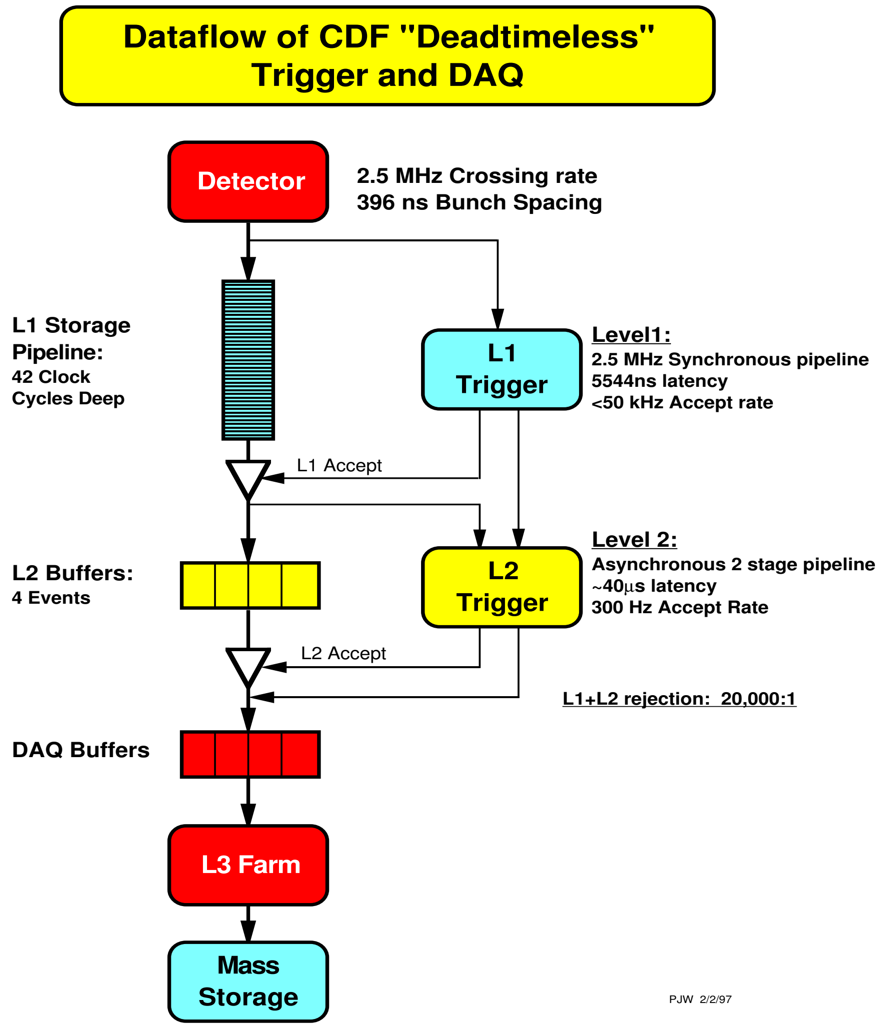








CDF Data Flow



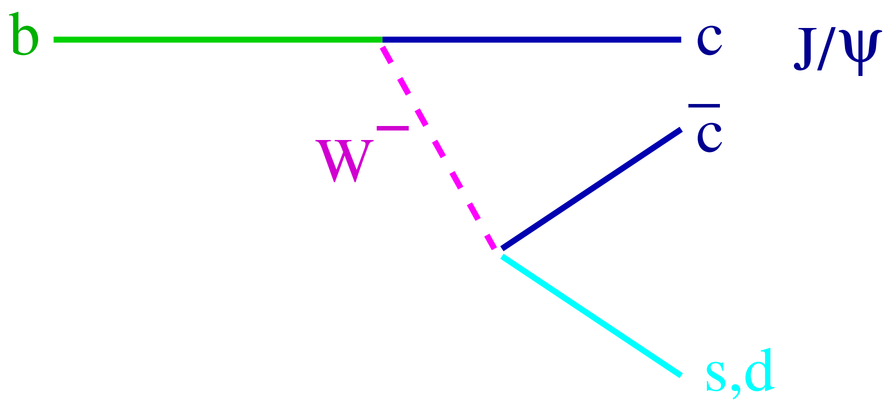
250 pb $^{-1}$ $\Rightarrow$ 480TB on tape

L1 latency: Pipeline depth = L1 processing time $\sim$ 5μsecs. *The SVXII detector is readout on L1 Accept*.

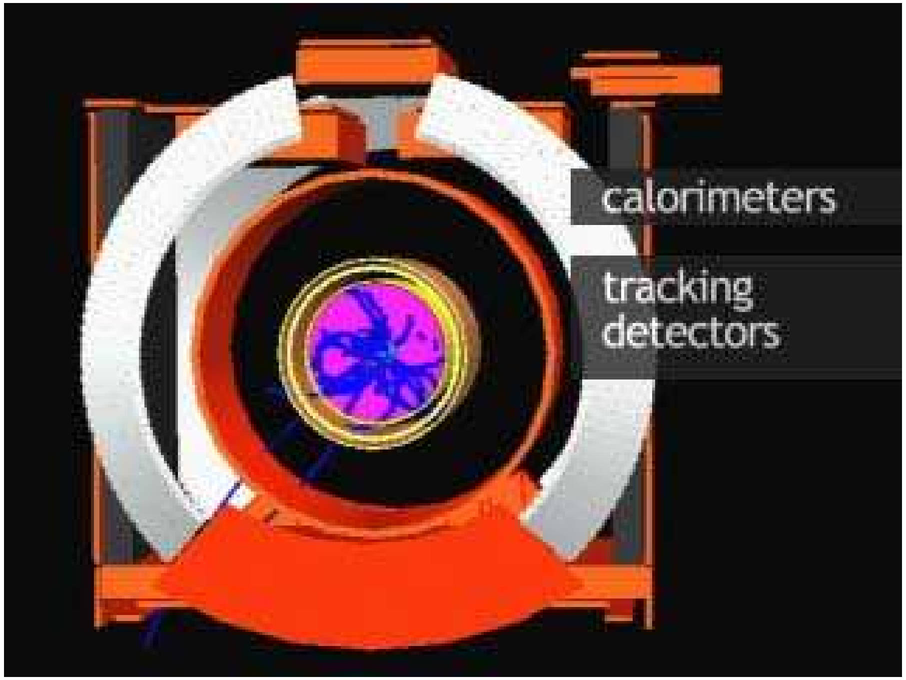
L2 processing time: The Silicon Vertex Trigger is in L2 $\Rightarrow$ *readout of the Silicon takes place in $\sim 15\mu$secs + $\sim 15\mu$secs SVT processing time*

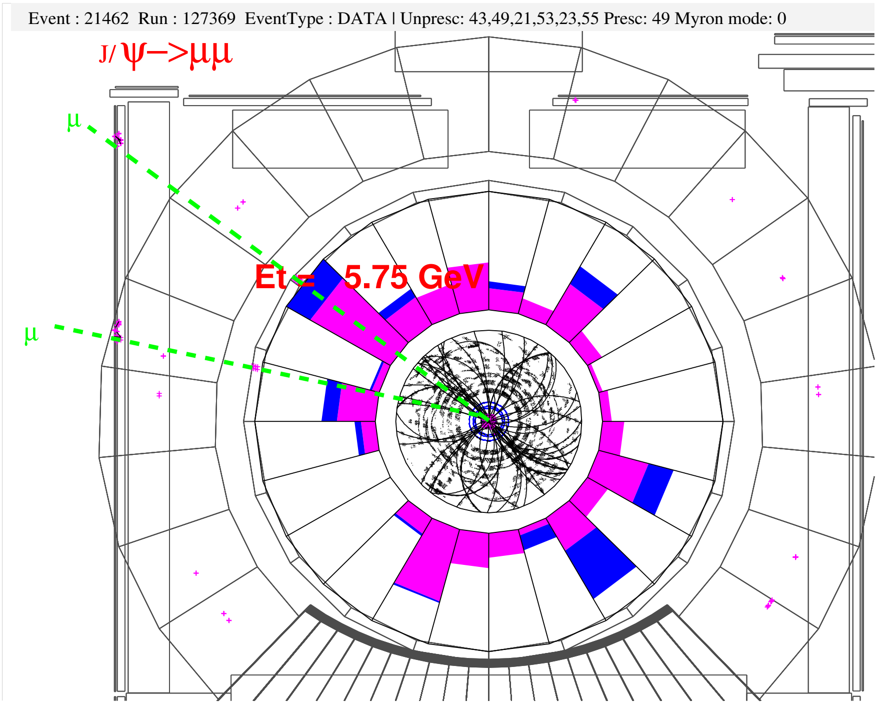
Data logging rate: sustained rate of 18MB/s (150-200 KB/event)

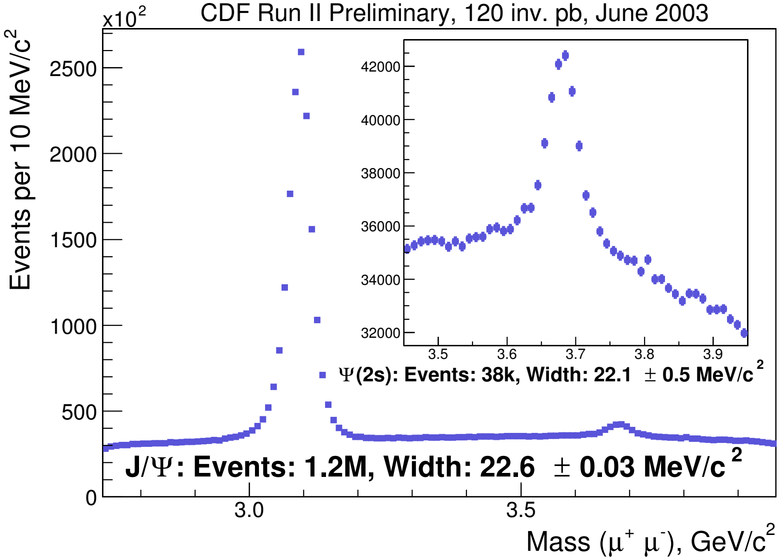
RUN II MEASUREMENT OF THE J/ψ AND b-HADRON INCLUSIVE CROSS-SECTIONS



Event Snapshot - $J/\psi \to \mu\mu$ event

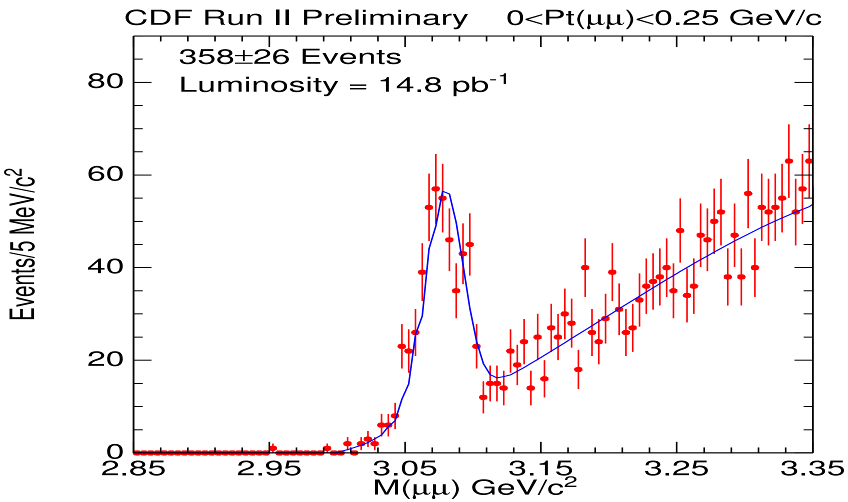




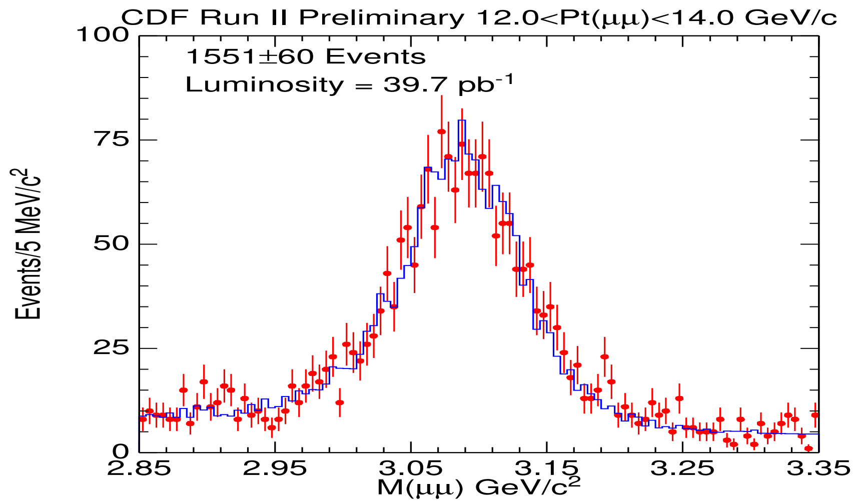


Counting J/ψs ($p_T = 0$ to 20 GeV/c)

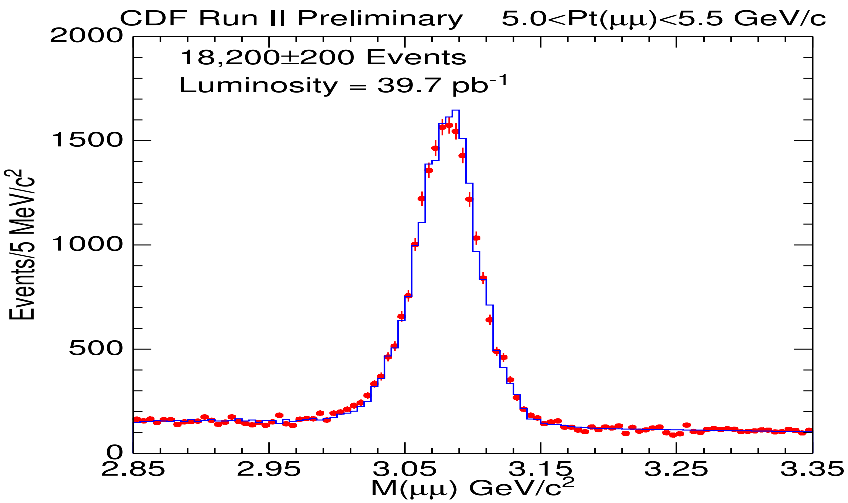
$0 < p_T(J/\psi) < 0.25 GeV/c$



$12 < p_T(J/\psi) < 14 GeV/c$



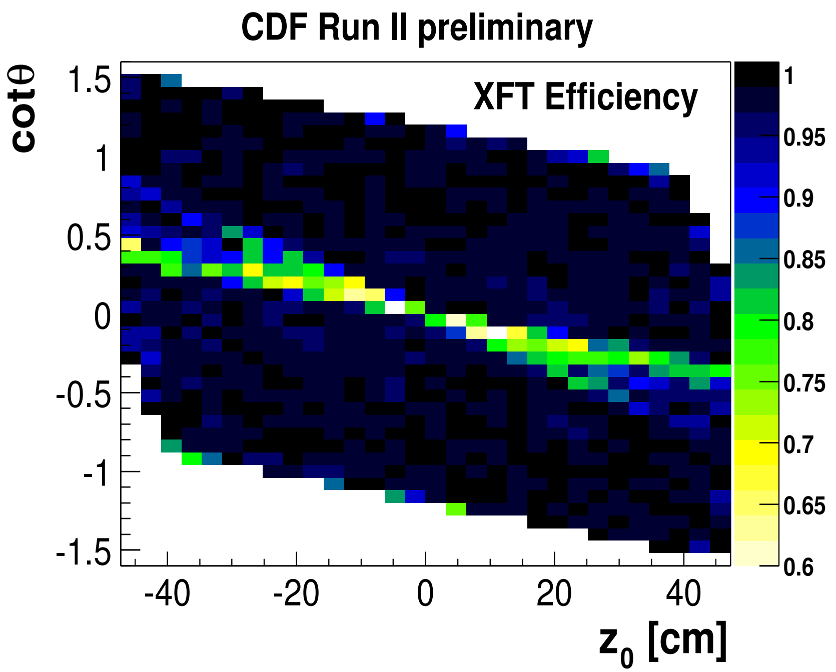
$5 < p_T(J/\psi) < 5.5 GeV/c$



- Transverse momentum resolution: $\delta(p_T)/p_T = 0.003 p_T$
- A detector simulation is used to model the expected shape of the J/ψ signal.

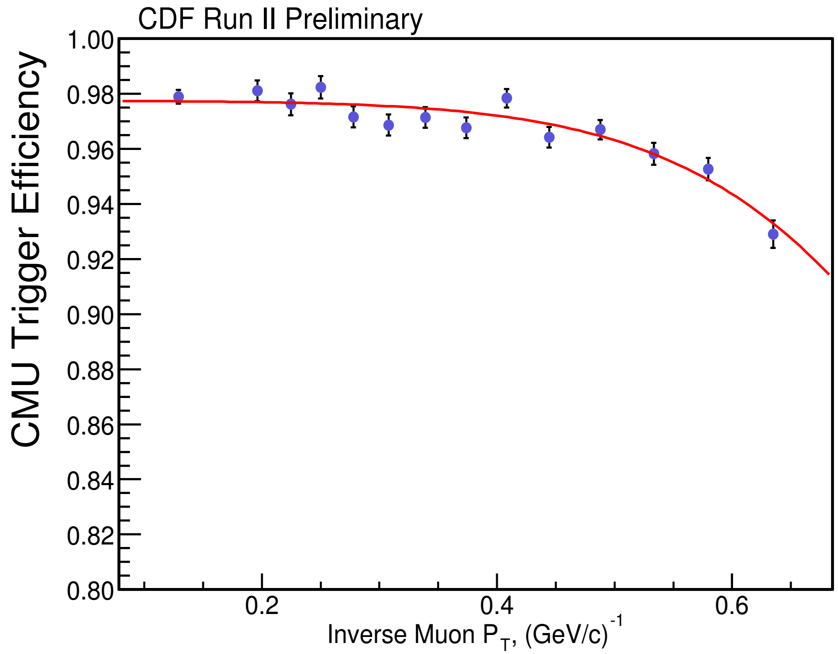
Muon Trigger efficiency

Level 1 tracking efficiency



Inefficient near center of wire planes

L1 muon trigger efficiency .vs. $1/p_T$

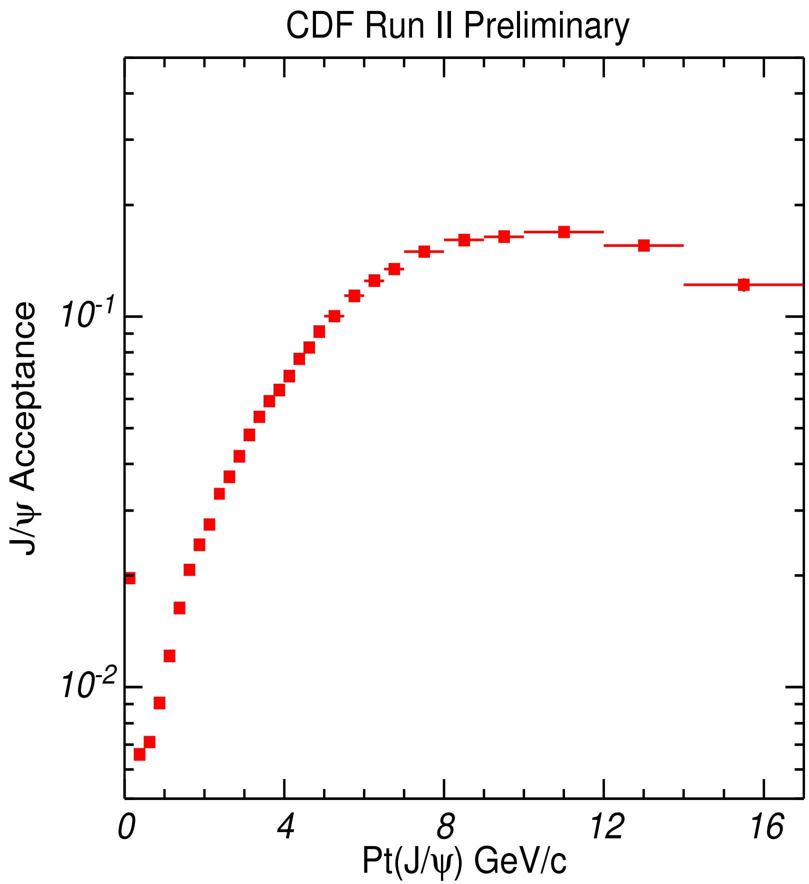


After excluding inefficient region

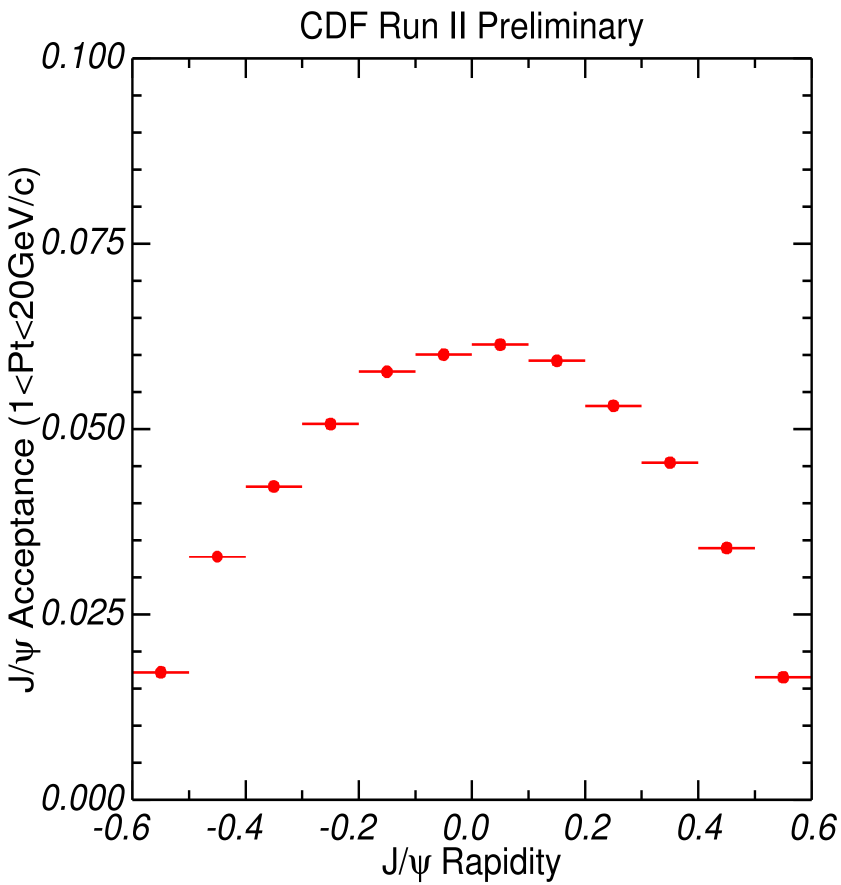
- Level 1 single μ trigger efficiency at 1.5 GeV/c is 92%
- Plateau is at 98 % except for tracks passing within 1.5 cm of the center of the COT wire plane where spacers are located

Detector Acceptance

A detector simulation is used to estimate acceptance:



Transverse momentum

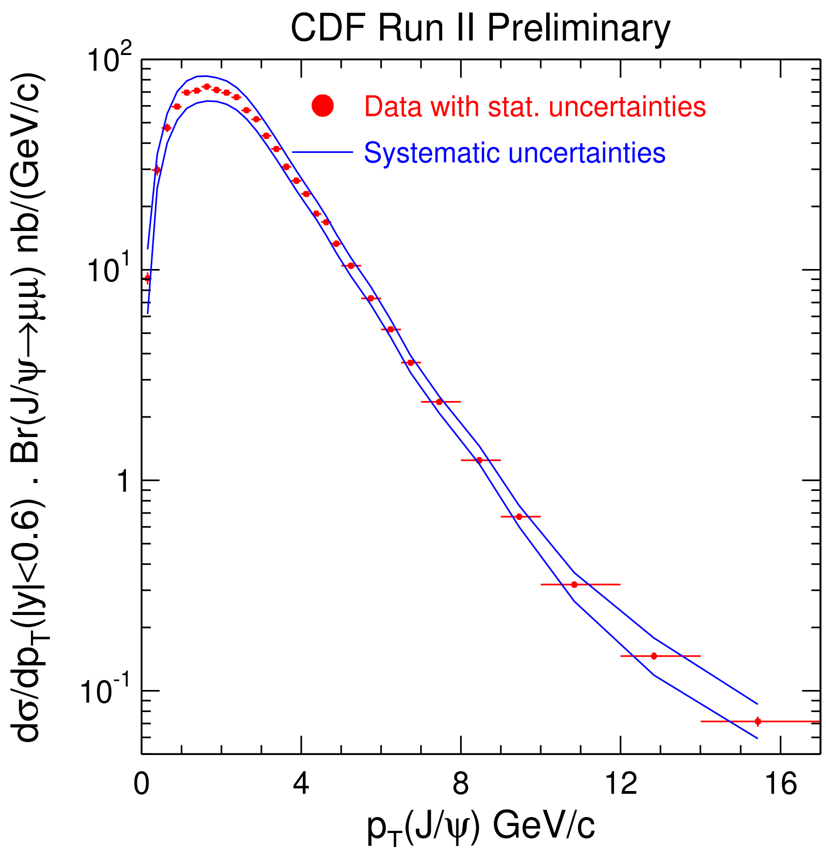


Rapidity

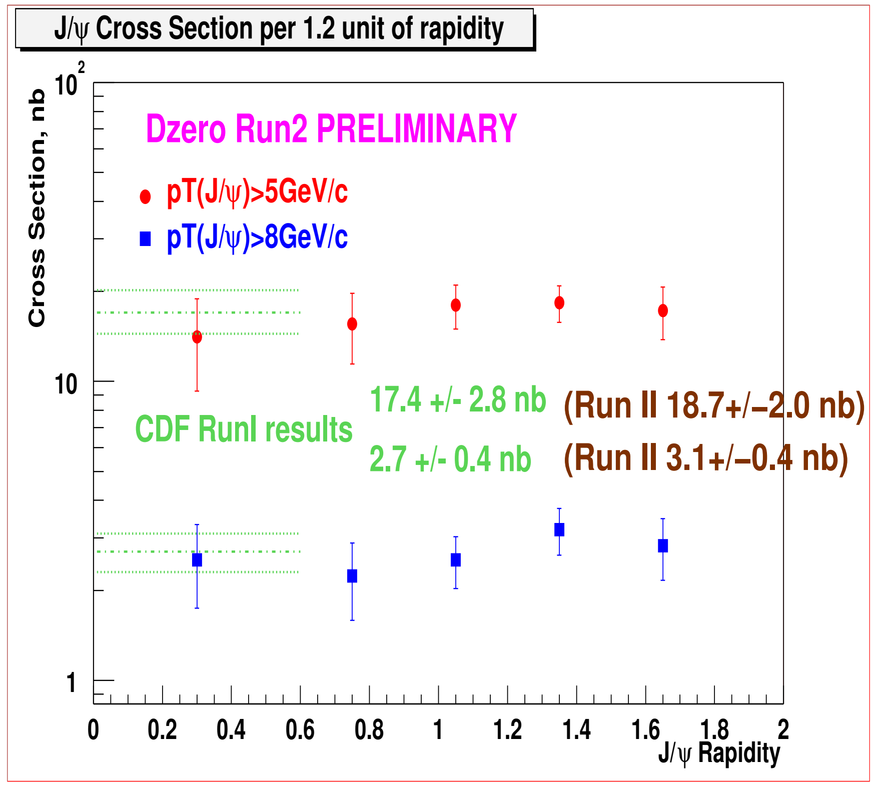
J/ψ Cross-sections - Run II

$$\frac{d\sigma(p\bar{p}\rightarrow J/\psi X)}{dp_T(J/\psi)} = \frac{\text{Number of } J/\psi}{\text{luminosity}\times\text{acceptance}\times\text{efficiency}\times\Delta p_T}$$

$\sigma(p\bar{p} \rightarrow J/\psi X, |y| < 0.6)$ vs $p_T(J/\psi)$



$\sigma(p\bar{p} \rightarrow J/\psi X, p_T > 5, 8 GeV/c)$ vs $y(J/\psi)$

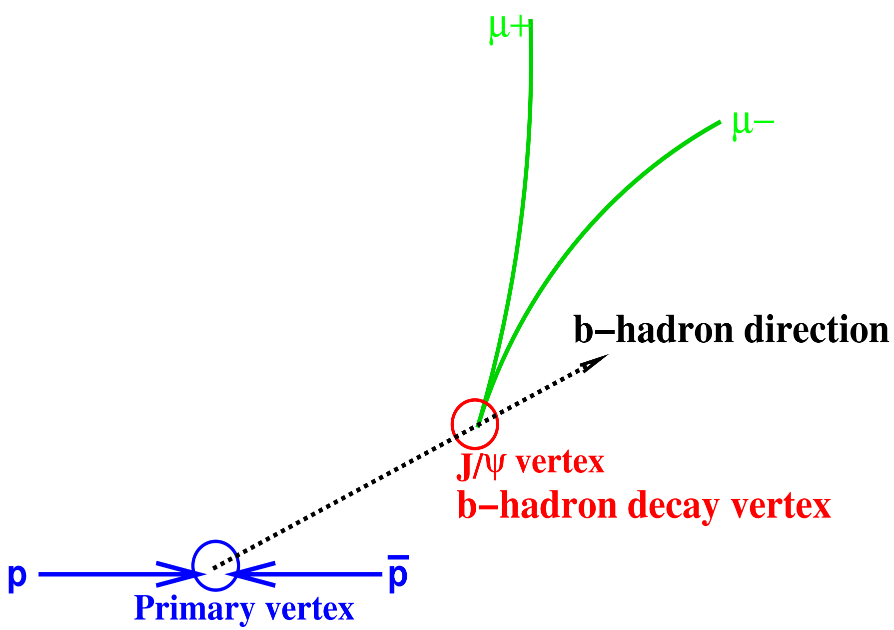


$$\sigma(p\bar{p} \rightarrow J/\psi X, |\, y(J/\psi)\, | < 0.6) = 4.08 \pm 0.02(stat)^{+0.60}_{-0.48}(syst)\ \mu\text{b}$$

Run I $\sigma(p\bar{p} \rightarrow J/\psi X, |\, \eta(J/\psi)\, | < 0.6) = 0.30 \pm 0.05 \mu\text{b}$

Separate $H_b \to J/\psi X$ from Total

- The J/ψ inclusive cross-section includes contributions from
  - Direct production of J/ψ
  - Indirect production from decays of excited charmonium states such as $\psi(2S) \to J/\psi(1S)\pi^+\pi^-$
  - Decays of b-hadrons such as $B \to J/\psi X$

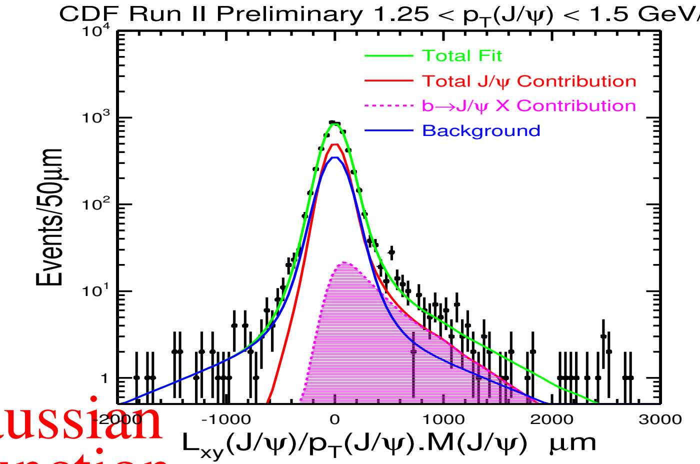


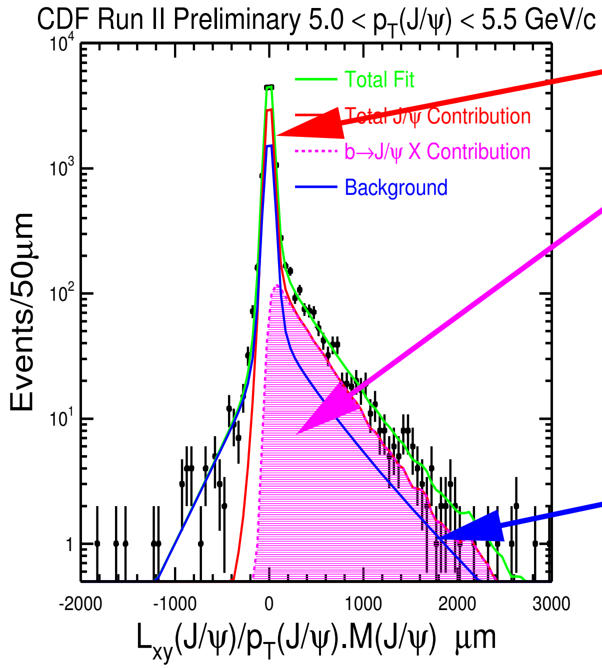
- b-hadrons have long lifetimes ($\tau = 1.56 ps, c\tau = 468\mu$m), $\Rightarrow J/\psi \to \mu\mu$ vertices from $H_b \to J/\psi X$ decays will be displaced from the primary interaction point.

Extracting the b-fraction

- A maximum likelihood fit to the flight path of the J/ψ in the $r - \phi$ plane, L_{xy} is used to extract the b-fraction.

$1.25 < p_T < 1.5$ GeV/c, $f_b = 9.7\%$



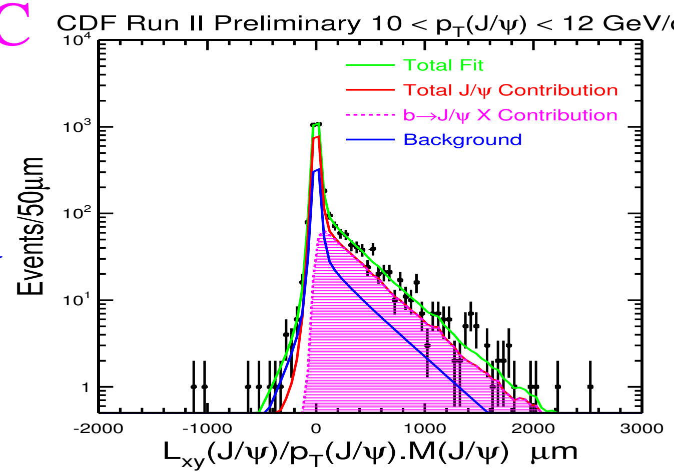


Prompt J/Ψ is a double Gaussian = resolution function

b–>J/Ψ X shape from MC template

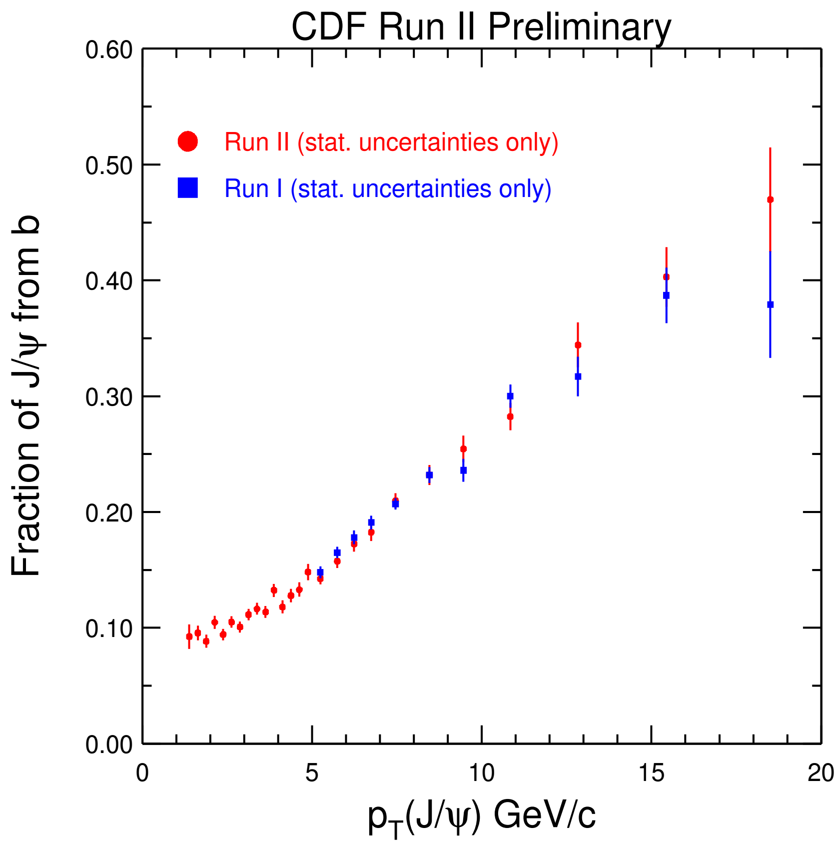
Parameterized background

$10 < p_T < 12$ GeV/c, $f_b = 28\%$

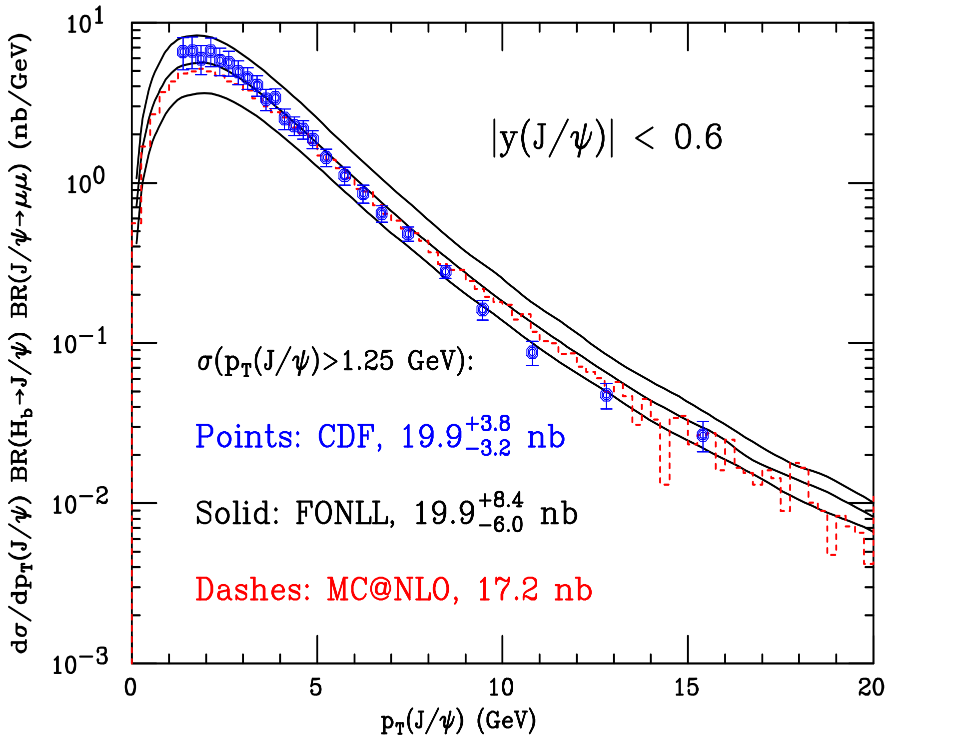


$d\sigma(p\bar{p} \to H_b X)/dp_T(J/\psi)$

Fraction of J/ψs from H_b



$d\sigma(p\bar{p} \to H_b X, H_b \to J/\psi X)/dp_T(J/\psi)$



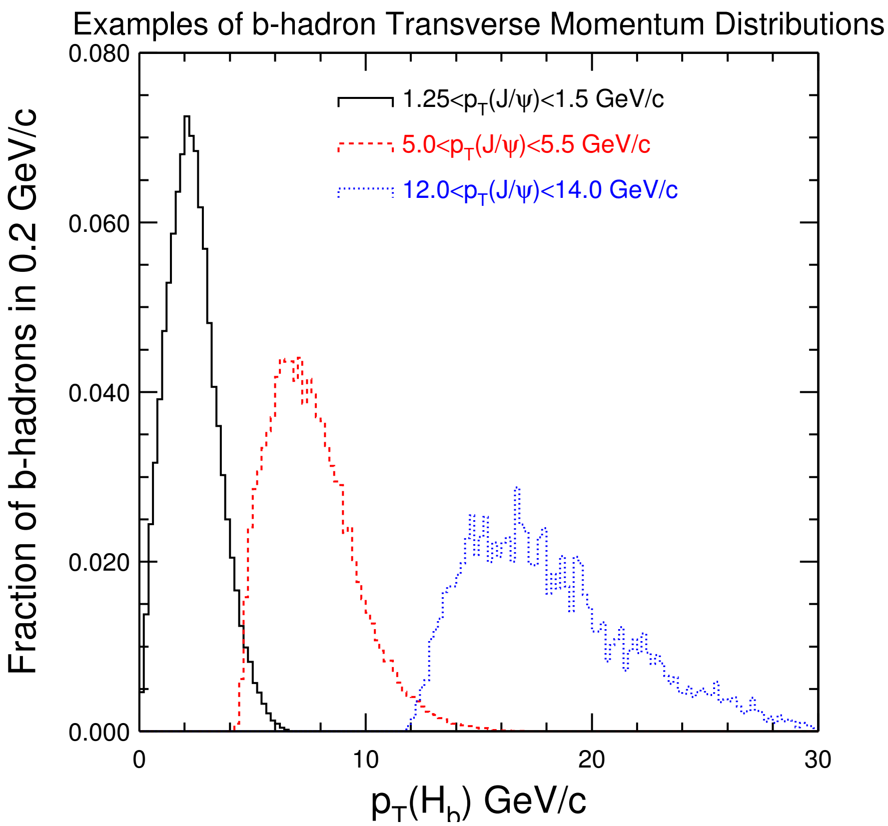
Theory: M.Cacciari, S. Frixione, M.L. Mangano, P. Nason. G. Ridolfi (Dec, 2003)

Algorithm to extract $d\sigma/dp_T(H_b)$

- Count the observed number of b-hadrons in a given $p_T(H_b)$ bin

$$N_i^b = \sum_{j=1}^{N} w_{ij} N_j^{J/\psi}$$

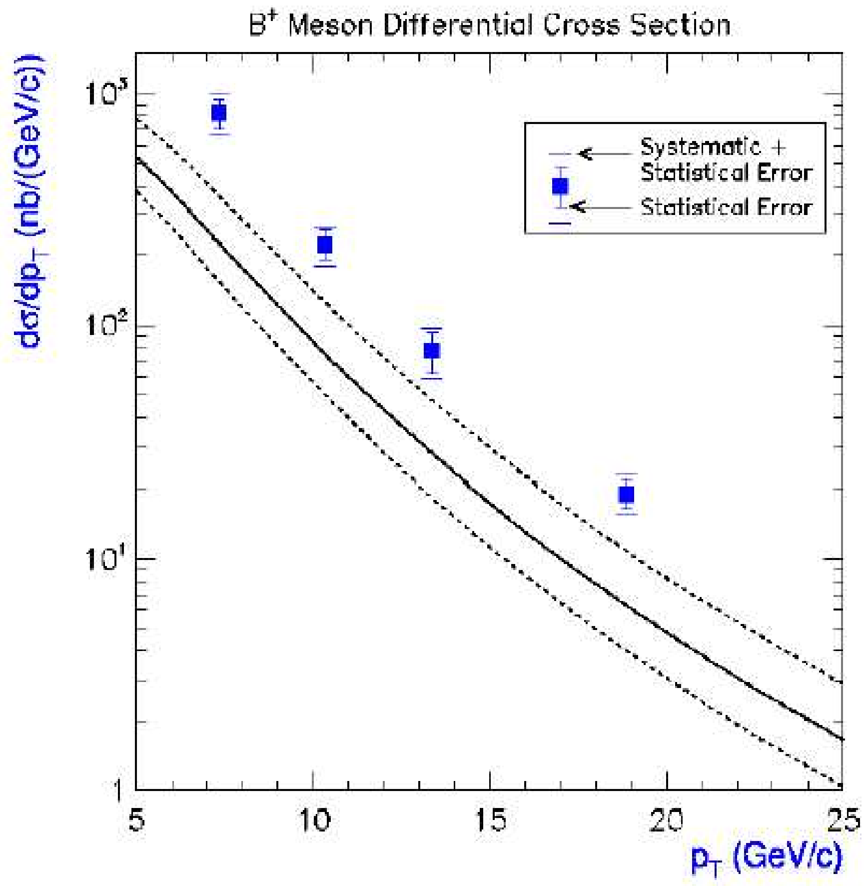
w_{ij} is the fraction of b events in the i^{th} $p_T(H_b)$ from the j^{th} $p_T(J/\psi)$ bin obtained from MC.



- Correct the observed number of b-hadrons for the kinematic acceptance

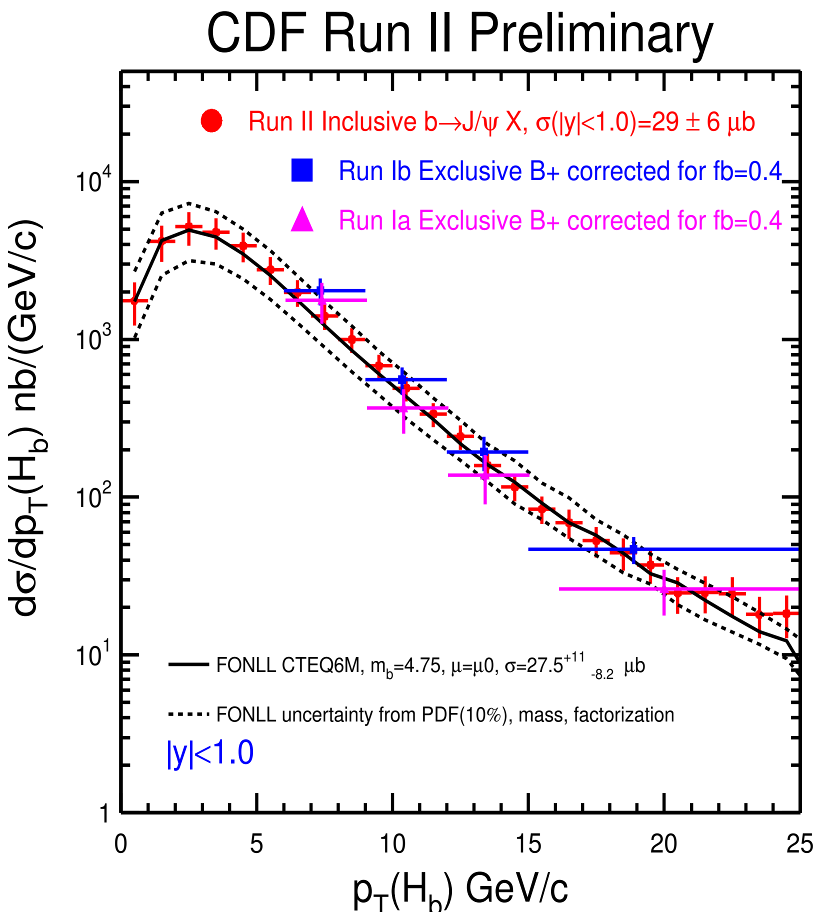
b-Production cross-section

$\sigma(p\bar{p} \to B^+ X)$ vs $(p_T(B^+))$



1997

$\sigma(p\bar{p} \to bx)$ versus $(p_T(H_b))$



2003

Data: $\sigma = 29 \pm 6\mu$b, THEORY: $\sigma = 27.5^{+11}_{-8.2}\mu$b (CTEQ6M, $m_b = 4.75$, $\mu = \mu_0$)

Summary

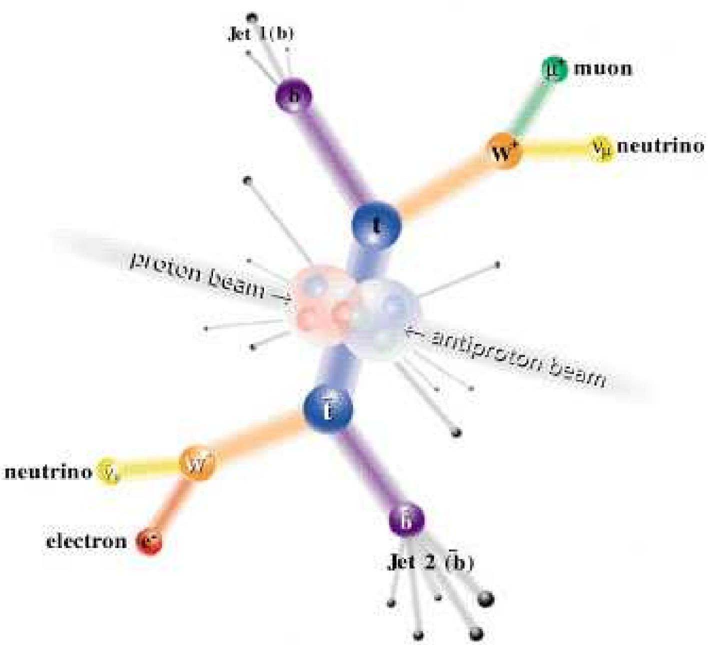
Studies of heavy quark production are precision tests of QCD.

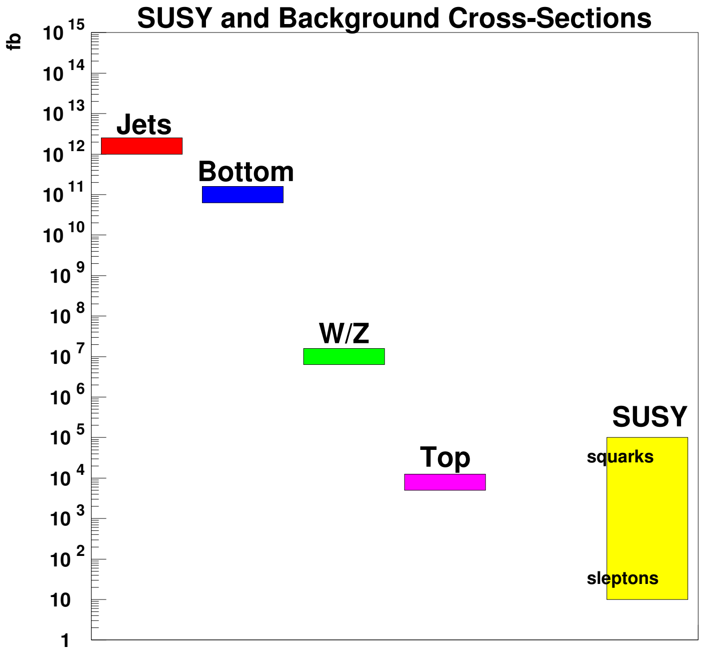
- NEW data in 2003:
  - In 2003, new measurements of the inclusive central J/ψ cross-sections and the inclusive central b cross-sections down to $p_T = 0$ GeV/c have been carried out at CDF. *These are the first measurements down to $p_T = 0$ GeV/c at a hadron collider*.
- Lots of theory advances since 1997:
  - New PDF fits to proton structure data.
  - Improved theoretical description of b fragmentation.

Total inclusive b-hadron cross-sections are in reasonable agreement with theoretical predictions within uncertainties.

The role of $\sigma(p\bar{p} \rightarrow H_b X)$ in HEP

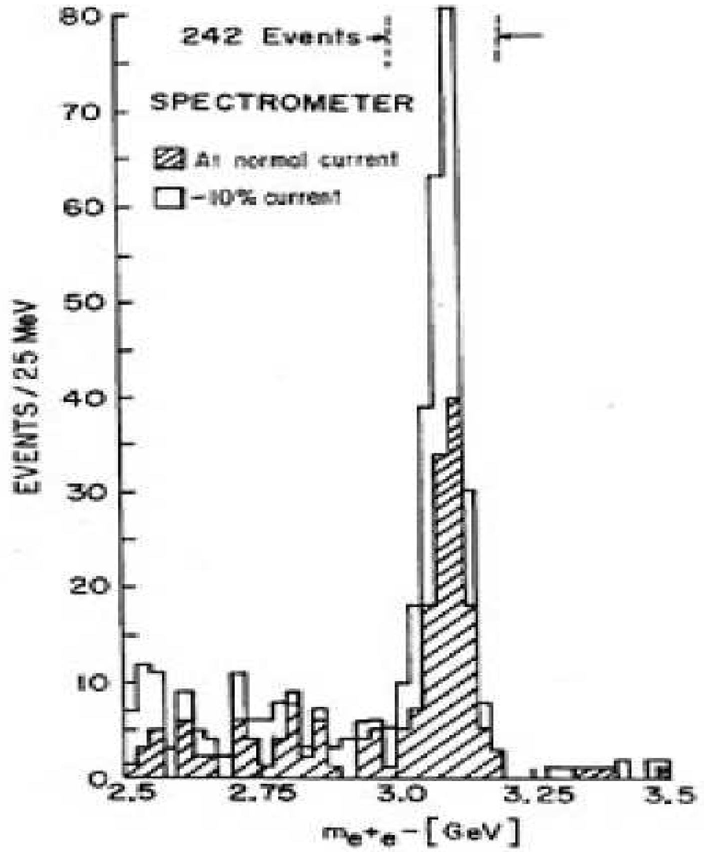
- Precision cross-section measurements are sensitive to new physics beyond the standard model.
- Charm and Beauty production dominates at hadron colliders and form huge backgrounds to Top and new physics searches which involve b quarks in the final state.





BACKUP

QUARKONIA PRODUCTION

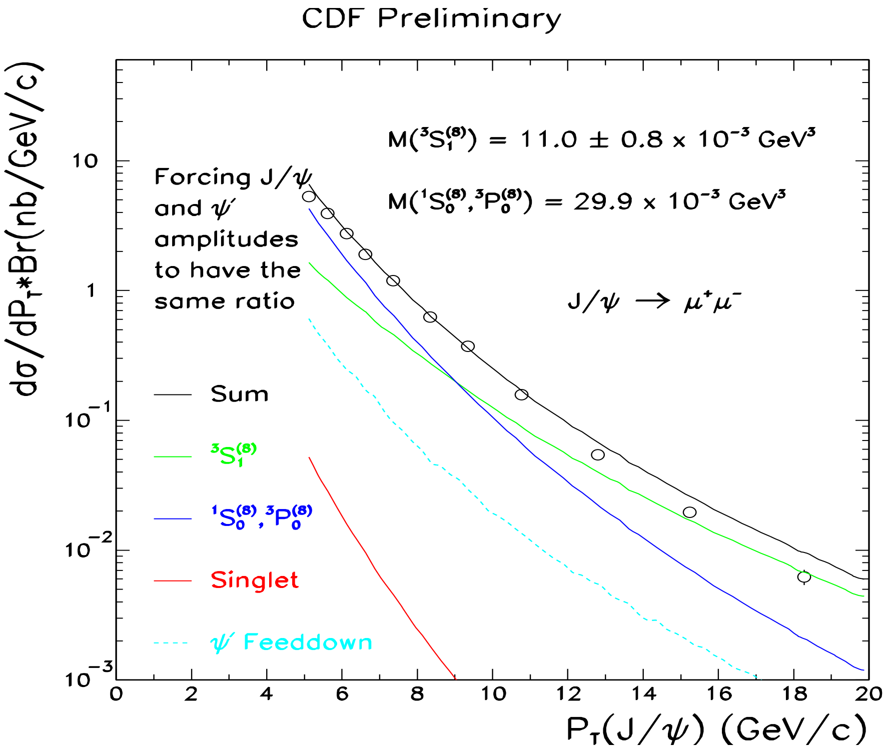


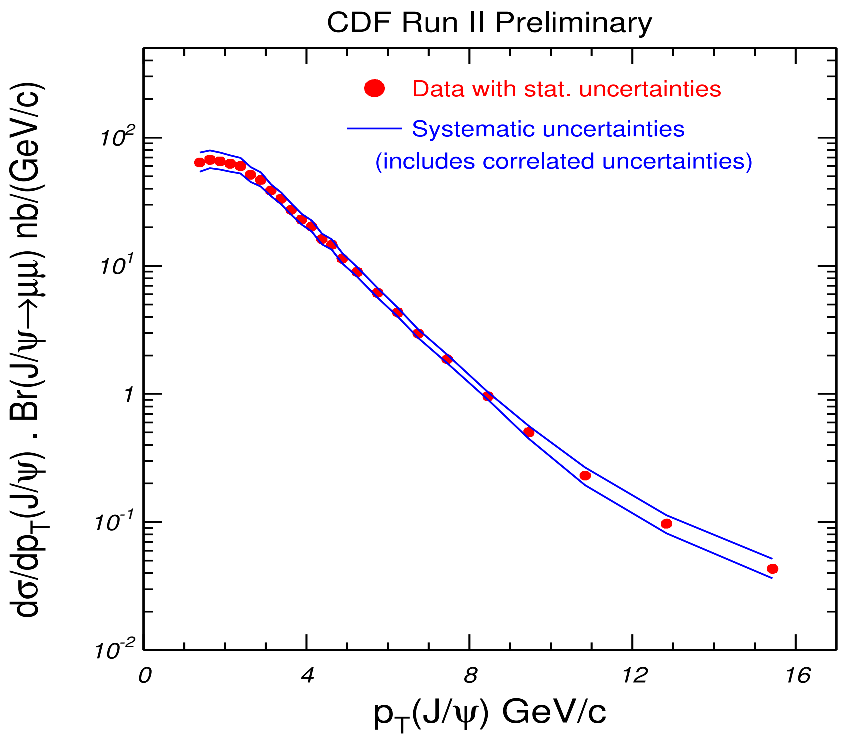
Quarkonia = discovery. J/ψ signal at Brookhaven in 1974

Prompt Quarkonia Production

Quarkonia bound states are non-relativistic. NRQCD LO perturbative expansion is $\mathcal{O}(\alpha_s^3 v^0)$ as in the color singlet model (CSM) + higher order $\mathcal{O}(\alpha_s^3 v^4)$.

Fragmentation processes $\propto$ color octet matrix element dominate. CO matrix elements extracted from fits to data - agree well with Run I data at high p_t.

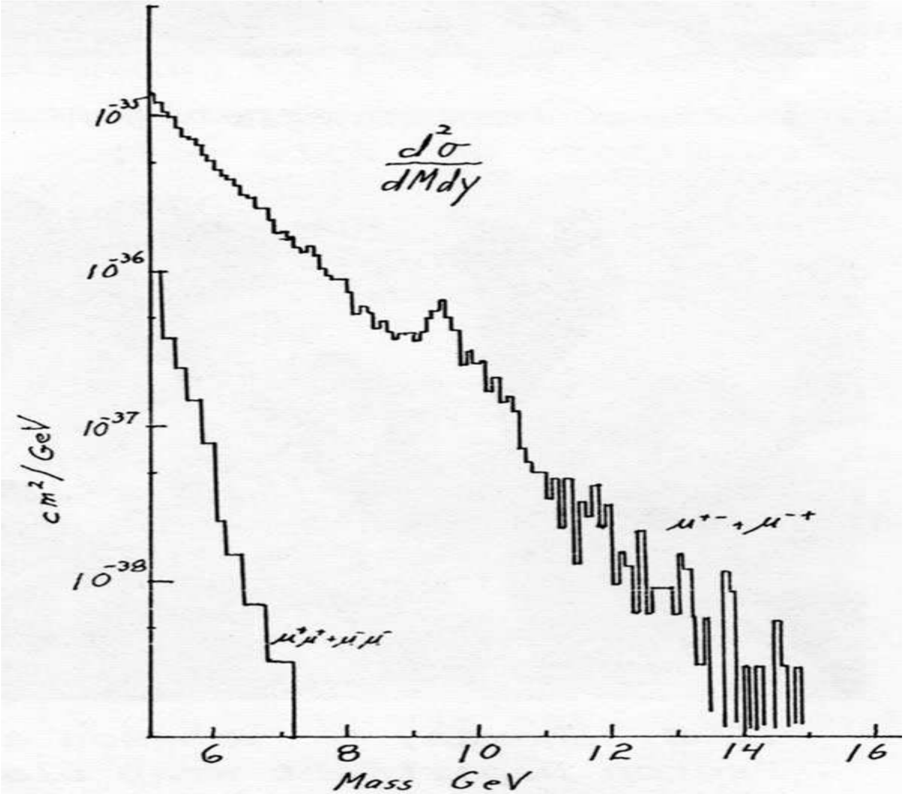




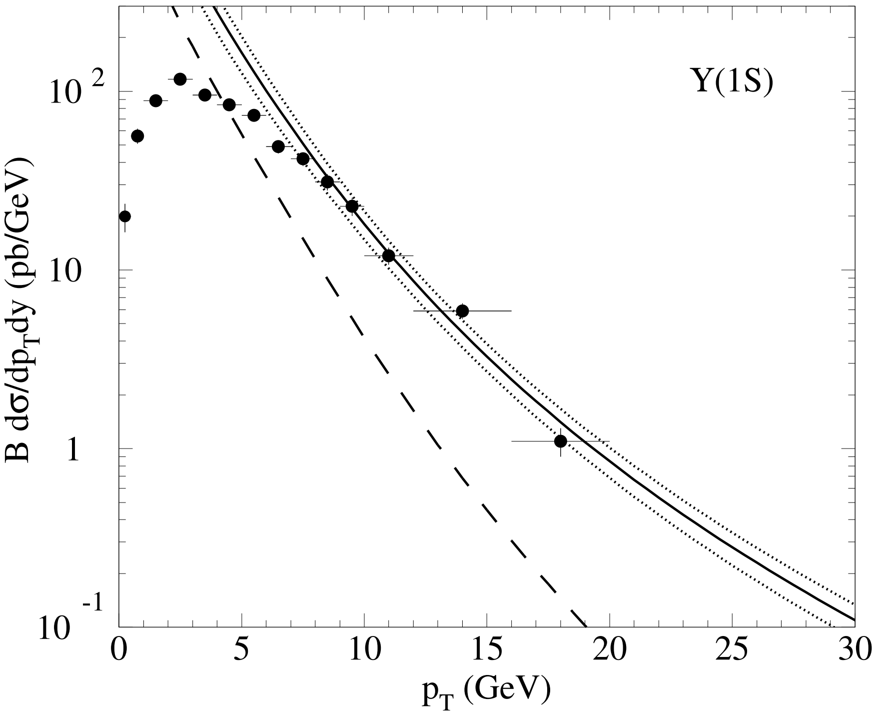
Prompt J/ψ production (Run I) Prompt J/ψ production (Run II)

Back to Υs!

At lower p_t NRQCD non-fragmentation diagrams from other octet matrix elements are important, soft gluon effects cause rates to diverge.



Υ discovery (1977)



$\Upsilon(1S)$ production (Run I)

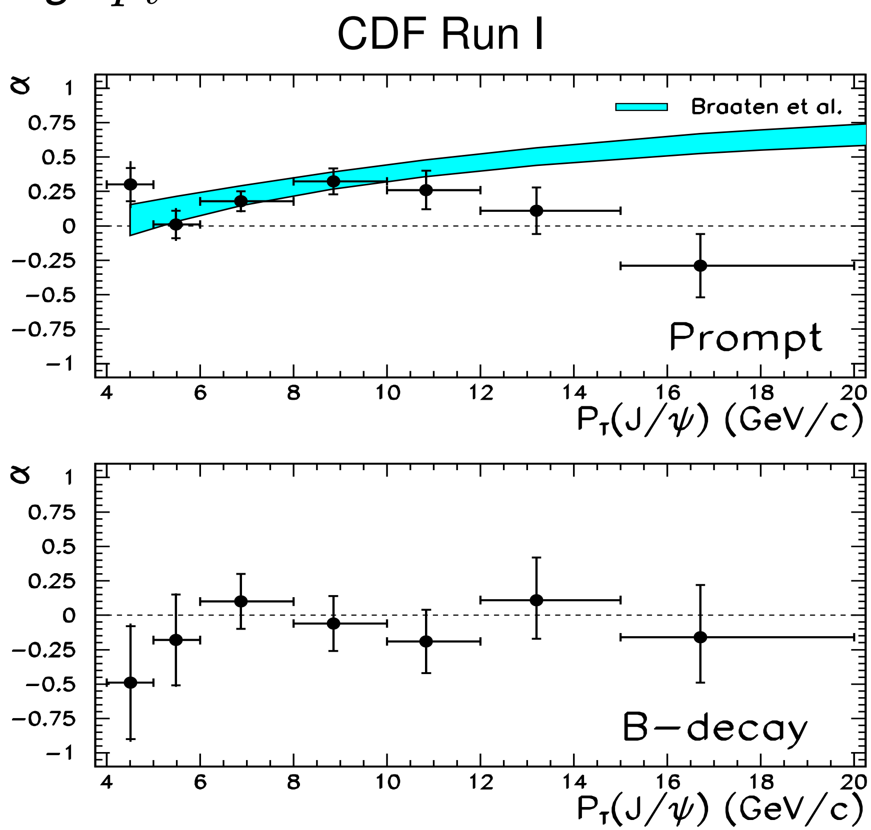
No new theoretical predictions for low p_T quarkonium at $p\bar{p}$ yet. BUT: resummation of color octet matrix elements possible by summer 2004.

Charmonium Polarization Mystery

BUT Inclusion of color octet in NRQCD leads to a prediction of increasing transverse polarization of charmonium at high p_t.

Method: Fit the production angle, $\cos\theta*$, distribution to MC distribution which is a mixture of transverse and longitudinal polarizations. Use lifetime fit method to separate prompt and $b \to J/\psi X$

$dN/d\cos\theta^* \propto (1 + \alpha\cos^2\theta^*)$



Run II :Need more precise measurements

N.B. Accurate measurements needed to reduce systematic uncertainty on detector acceptance

OTHER INTERESTING PRODUCTION TIDBITS

High p_T b-Jet Production

- b-jets include much of the quark fragmentation remnants $\Rightarrow$ jet cross-sections have small dependence on fragmentation.